

Chapter 5

OBJECTIVES

Terminal Learning Objective

At the end of this chapter, the student will be able to identify the basics of absorbers.

Enabling Learning Objectives

- 5.1 Distinguish amongst the various types of absorbers
- 5.2 Identify the principles of operation that influence the efficiency of absorbers.
- 5.3 Determine the capability and sizing parameters of an absorber system.
- 5.4 Identify the instrumentation requirements for an absorber system.

Absorption

Absorbers in air pollution control applications use aqueous scrubbing liquids to remove gases and vapors. Absorber design has benefited substantially from the extensive development of these types of systems for non-pollution-control process applications and is, therefore, a relatively mature technical field.

The use of absorbers has increased since 1990 because of increased concerns about gaseous contaminants, which are classified as air toxic or volatile organic compounds (VOCs). In addition to stand-alone systems, absorbers are frequently used downstream of thermal and catalytic incinerators to remove acid gases generated from the combustion of sulfur-containing and/or halogenated compounds present in the incinerator feed.

Absorption refers to the transfer of a gaseous component from the gas phase to a liquid phase. The opposite operation, known as stripping, involves the transfer of the contaminant from the liquid to the gas phase and is important in water pollution control applications. Absorption occurs into liquid droplets dispersed in the gas stream, sheets of liquid covering packing material, or jets of liquid within the vessel. The liquid surface area available for mass transfer and the time available for diffusion of the gaseous molecules into the liquid are important factors affecting performance. Absorption can be divided into two broad classifications: straight dissolution of *absorbate* (contaminant gas) into *absorbent* (liquid), and dissolution accompanied by irreversible chemical reaction. This chapter covers only straight dissolution. Dissolution accompanied by chemical reaction, which is important in air pollution control applications such as flue gas desulfurization, is covered in a later chapter.

The gaseous contaminant being absorbed (absorbate) must be at least slightly soluble in the scrubbing liquid (absorbent). Mass transfer to the liquid continues until the liquid approaches saturation. At saturation, equilibrium is established between the two phases. The mass transfer rate of the contaminant into the liquid is equal to the mass transfer rate of the dissolved species back into the gas phase. Accordingly, the solubility of the contaminant in the liquid creates a limit to the amount of pollutant removal that can occur with a given quantity of liquid. This solubility limit can be overcome by providing reactants in the liquid phase that react with the dissolved gas contaminant, forming a dissolved compound

that cannot exit the liquid. This is the case in flue gas desulfurization, where a compound that reacts irreversibly with SO_2 , such as CaO , is added to the liquid.

5.1 Types and Components of Absorbers

Types of Absorbers

Spray-Tower Absorbers

Spray towers are the simplest devices used for gas absorption. They consist of an open vessel and one or more sets of liquid spray nozzles to distribute the scrubbing liquid (absorbent). Typically, the flow is countercurrent, with the contaminant gas stream entering near the bottom of the tower and flowing upward, while the liquid enters near the top and flows downward. The most dilute gas is exposed to the most dilute liquid at the top of the column while the most concentrated gas and liquid are in contact near the bottom. Figure 5-1 illustrates a typical countercurrent-flow spray-tower absorber. Spray towers range in size from 5 to 100,000 ACFM (0.14 to 2800 m^3/min).

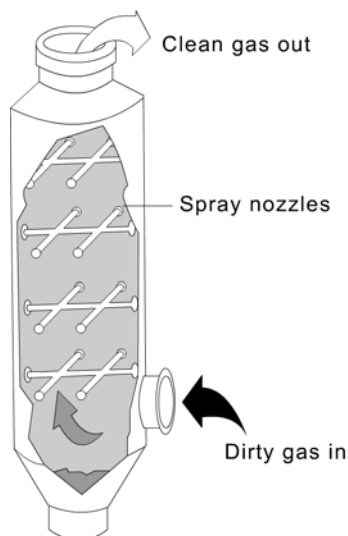


Figure 5-1. Counter-current spray-tower scrubber.

Spray chambers can also operate in cross-current or co-current flow arrangements when there is limited space in an industrial facility. In cross-current absorbers, the gas flow is perpendicular to the liquid flow. In co-current absorbers, the gas and liquid flow in the same direction. Because the gas stream does not “push” against the liquid stream as in countercurrent flow, higher gas stream velocities can be used. With higher gas stream velocities, the size of the unit can be reduced. However, cross-current or co-current spray towers are not usually as efficient as countercurrent units.

The liquid is distributed through a series of spray nozzles. Full-cone nozzles are generally used. The full-cone nozzle generates a spray pattern that completely fills the target area, as shown in Figure 5-2. The spray angle is a function of the liquid pressure in the supply header.

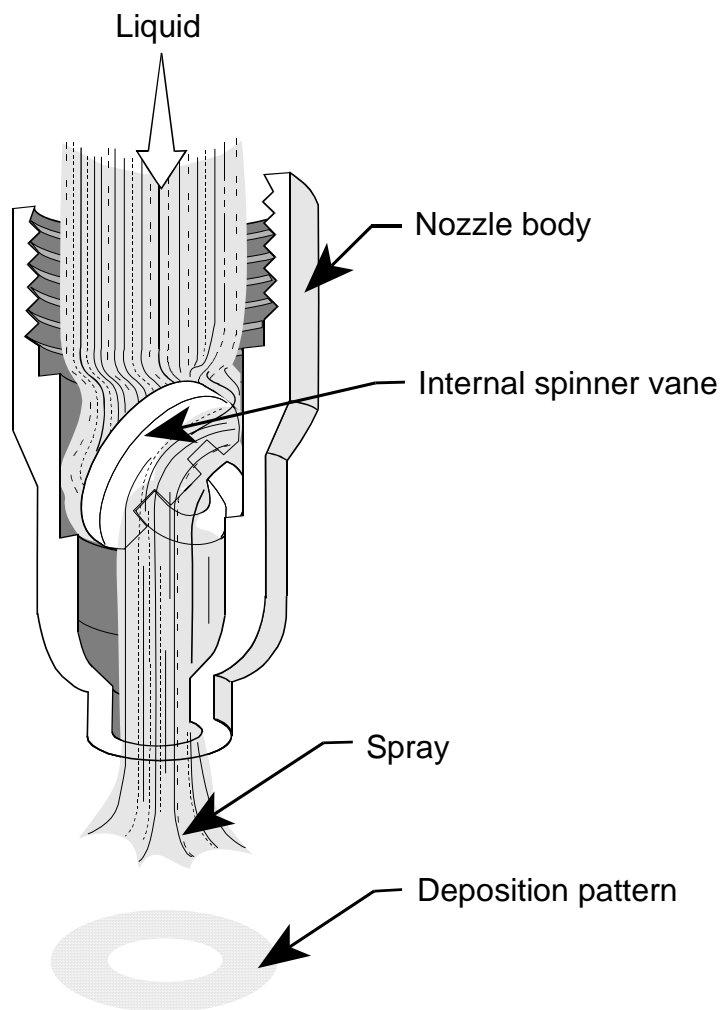


Figure 5-2. Full-cone spray nozzle.

The quantity of liquid, normally characterized by the liquid-to-gas ratio (L/G), is a key parameter in gas absorption. The (L/G) is frequently expressed in units of gallons per minute of liquid divided by the gas flow rate in units of 1000 ACFM.

Typical (L/G) ratios for spray-tower absorbers can vary from 5 to more than 50 gallons per 1000 ACF. The (L/G) is determined by the solubility of the contaminant in the liquid and by the mass transfer characteristics in the spray tower. Contaminant capture efficiency increases with increasing (L/G) and one important aspect of the design problem amounts to determining the optimum (L/G) required to satisfy emission specifications at the minimum cost.

Because of limited contact between the liquid droplets and the gas stream, spray-tower absorbers are used primarily in applications where the gases are extremely soluble in the absorbent, where high pollutant removal efficiency is not required, or where the chemical reactions in the absorbing liquid could result in salts that could cause plugging in other types of absorber vessels. They have been used to control SiF_4 and HF generated in fertilizer plants during the production of superphosphate. Spray towers are also used in a number of flue gas desulfurization systems.

The main advantage of spray-tower absorbers is that they are completely open. They have no internal components except for the spray nozzles and connecting piping. Therefore, they have a very low gas-stream static pressure drop, which ranges from 1 to 3 in. W.C. (0.25 to 0.75 kPa) for the absorber vessel.

Mist eliminators, which are used to prevent liquid droplets from exiting the absorber with the gas stream, are used in all types of gas absorber equipment. Mist eliminators used in spray towers can add a 0.3 to 4 in. W.C. (0.075 to 1.0 kPa) to the total gas-phase static pressure drop.

Packed-Bed Absorbers

Packed-bed absorbers are the most common absorbers used for gas removal. The absorbing liquid is dispersed over the packing material, which provides a large surface area for gas-liquid contact. Packed beds are classified according to the relative direction of gas-to-liquid flow.

Types of Packed-Bed Absorbers. The most common packed-bed absorber is the countercurrent-flow tower shown in Figure 5-3. The gas stream enters the bottom of the tower and flows upward through the packing material and exits from the top after passing through a mist eliminator.

Liquid is introduced at the top of the packed bed by sprays or weirs and flows downward over the packing. In this manner, the most dilute gas contacts the least saturated absorbing liquid and the concentration difference between the liquid and gas phases, which is necessary for mass transfer, is reasonably constant through the column length. The maximum (L/G) in countercurrent flow is limited by flooding, which occurs when the upward force exerted by the gas is sufficient to prevent the liquid from flowing downward. The minimum (L/G) is fixed by the need to ensure that all of the packing is covered by a thin liquid film.

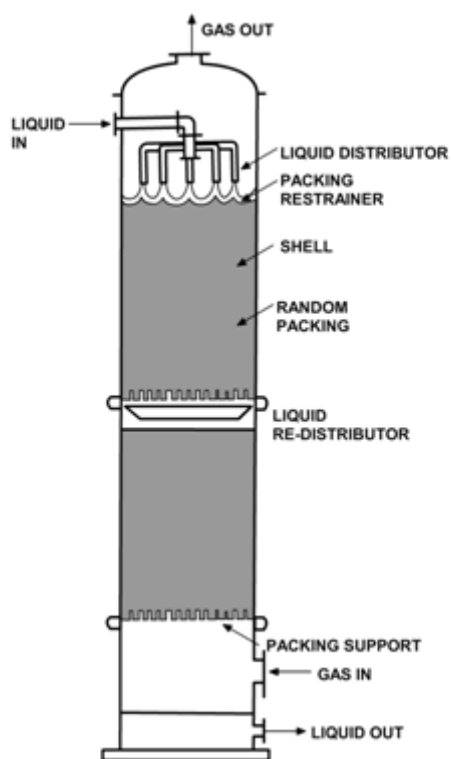


Figure 5-3. Countercurrent packed tower.

In a cross-flow absorber, the gas stream flows horizontally through the packed bed, which is irrigated by the scrubbing liquid flowing down through the packing material. A typical cross-flow absorber is shown in Figure 5-4. Inlet sprays aimed at the face of the bed may also be included. The leading face of the packed bed is often slanted in the direction of the incoming gas stream, as shown in Figure 5-4. The force exerted by the gas stream deflects the liquid from straight downward flow. Slanting the bed allows for this deflection and ensures complete wetting of the packing.

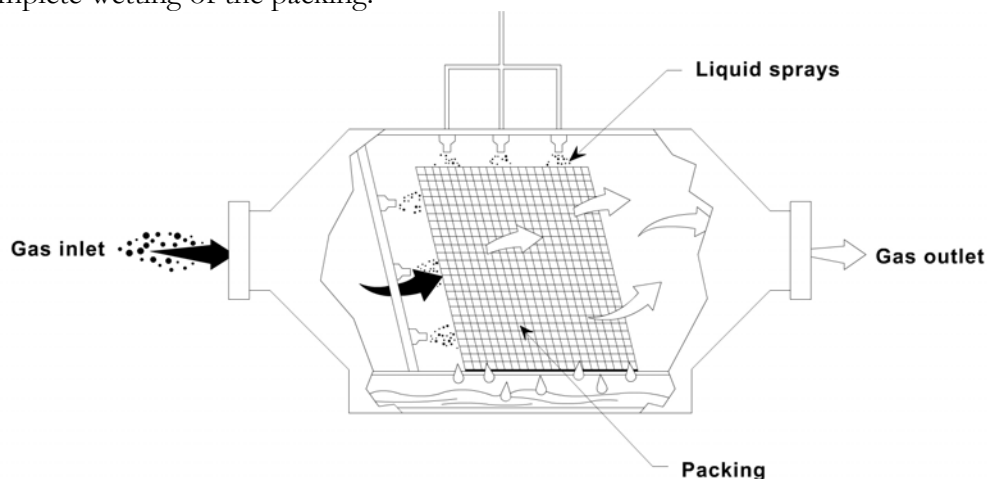


Figure 5-4. Flowchart of cross-flow scrubber.

The design procedure for cross-flow absorbers is more complex because concentration gradients exist in two directions: from top to bottom and from front to rear.

Gas-phase static pressure drop in packed bed absorbers ranges from 0.25 to 1 in. W.C. per ft of packing (0.06 to 0.25 kPa. per meter of packing) when the unit operates at typical gas flow rates. Large variations in liquid or gas flow rates cause loading and flooding of this type of absorber.

Packed-bed absorbers are most suited to applications where high gas-removal efficiency is required, and the feed gas stream is relatively free from particulate matter. In the production of both sulfuric and hydrochloric acids, packed bed absorbers are used to control tail and exhaust emissions (i.e., SO_2 and HCl , respectively). The scrubbing liquor for these processes can be a weak acid solution with the spent liquor from the packed tower sent back to the process. Packed towers are also used to control HCl and H_2SO_4 fume emissions from pickling operations in the primary metals industry. They are used to control odors in rendering plants, petroleum refineries, and sewage treatment plants. For odor control applications, the packed bed scrubbing liquor usually contains an oxidizing reagent, such as sodium hypochlorite. In these applications, an acid backwash must be added if a precipitate is formed or if plugging can be a problem. The gas flow rate through packed towers can vary from 5 to 30,000 ACFM (0.14 to 850 m^3/min).

Packing Material. The primary purpose of the packing material is to provide a large surface area for mass transfer. Figure 5-5 illustrates some of the most commonly used packings. These packings are usually made of plastic (polyethylene, polypropylene, or polyvinylchloride), but can be ceramic or metal. A specific packing is described by its trade name and overall size. For example, a column can be packed with 2-inch (5-centimeter) RaschigTM rings or 1-inch (2.5-centimeter) TellerettesTM. The overall dimensions of packing materials normally range from 1 to 4 inches (2.5 to 10.1 centimeters).

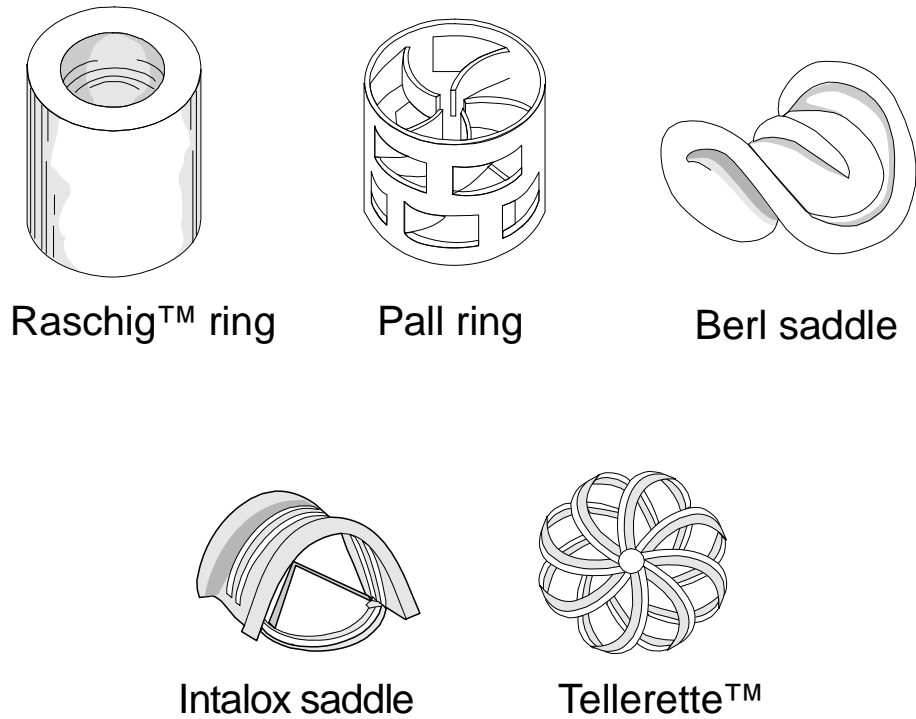


Figure 5-5. Types of packing.

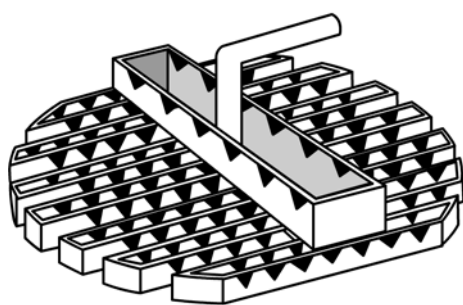
The specific packing selected depends on the corrosiveness of the contaminants and scrubbing liquid, the size of the absorber, the static pressure drop, and the cost. Specific considerations involved in the selection of packing materials are summarized below.

- **Cost.** Plastic packings are generally cheaper than metal, with ceramic being the most expensive.
- **Low pressure drop.** Pressure drop is a function of the volume of void space in a tower when filled with packing. Generally, the larger the packing size, the smaller the pressure drop.
- **Corrosion resistance.** Ceramic or porcelain packing is commonly used in a very corrosive atmosphere.
- **Structural strength.** Packing must be strong enough to withstand normal loads during installation, service, physical handling, and thermal fluctuations. Ceramic packing is subject to cracking under sudden temperature changes.
- **Weight.** Heavier packing may require additional support materials or heavier tower construction. Plastics are much lighter than either ceramic or metal packings.

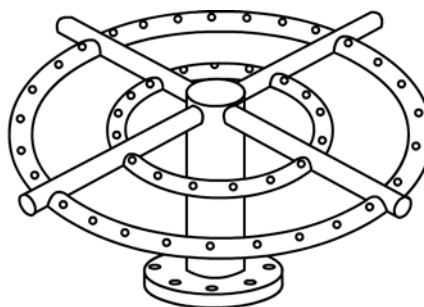
- **Design flexibility.** The efficiency of a scrubber changes as the liquid and gas flow rates are varied. Packing material must be able to handle the process changes without substantially affecting the removal efficiency.

Packing material may be arranged in an absorber in either of two ways. The packing may be dumped into the column randomly (as indicated in Figure 5-3) or stacked as structured material. Randomly packed towers provide a higher surface area per unit volume (ft^2/ft^3), but also cause a higher pressure drop than stacked packing. In addition to the lower pressure drop, the stacked packing provides better liquid distribution over the entire surface of the packing. However, the labor cost of installing stacked packing can be a major drawback, particularly for large systems.

Liquid Distribution. One of the requirements for efficient absorption is good gas-liquid contact throughout the entire packed bed. At the top of the column, liquid should be distributed over the entire upper surface of the packed bed. This is commonly achieved by the trough and weir or the perforated pipe arrangements shown in Figure 5-6, which provide flexibility with variations in liquid flow rate. Arrays of spray nozzles are also used.



(a) Trough and weir type



(b) Perforated pipe

Figure 5-6. Types of liquid distributors for packed-bed absorbers.

Once the liquid is distributed over the packing, it flows down by the force of gravity through the packing, following the path of least resistance. The liquid tends to flow toward the tower wall where the void spaces are greater than in the center. Once the liquid hits the wall, it flows straight down the tower (known as *channeling*). With taller columns, it is necessary to redirect the liquid from the tower wall back to the center of the column using liquid redistributors. Redistributors are usually placed at intervals of no more than 10 feet (3.1 meters), or 5 tower diameters, whichever is smaller.¹

Uniform distribution of the inlet gas stream is also important for achieving good gas-liquid contact. This is accomplished by properly designing the inlet gas ducts and the support trays that hold the packing material.

Tray-Tower Absorbers

A tray-tower absorber is a vertical column with one or more trays mounted horizontally inside for gas-liquid contact. The gas stream enters at the bottom and flows upward, passing through openings in the trays. Liquid enters at the top of the tower, and travels across each tray and then through a downcomer to the tray below until it reaches the bottom of the tower. Mass transfer occurs in the liquid spray created by the gas velocity through the openings in the tray. Figure 5-7 illustrates a typical bubble cap-tray tower unit. Note that Figure 5-7 shows the capability for the addition and removal of liquid at liquid at an intermediate position in the column. Such an arrangement would be unusual in pollution control applications.

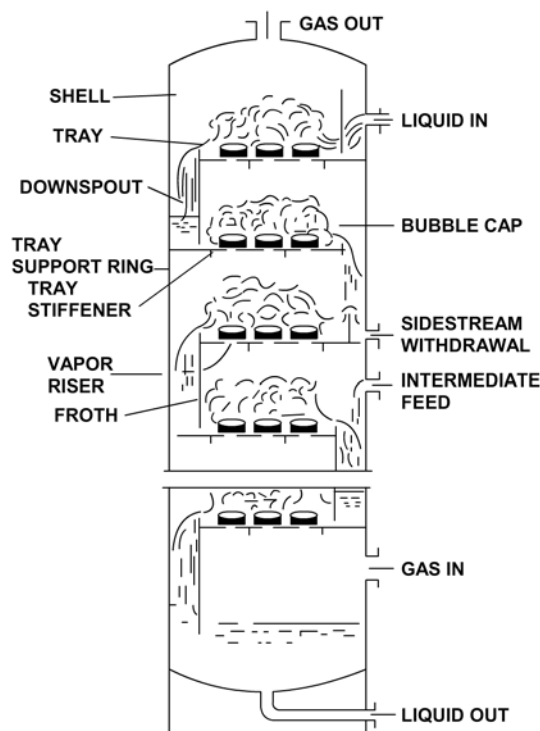


Figure 5-7. Bubble-cap tray.

The function of the trays is to provide a liquid depth through which the gas bubbles and creates liquid droplets, creating large gas-liquid interface areas for mass transfer. The depth of liquid on each tray is controlled by a weir at the position where liquid enters the downcomer. The pressure of the gas below each tray must be sufficient to prevent liquid droplets from falling through the openings in the trays, a condition known as *weeping*. A variety of different tray designs are used for air pollution control.

Bubble-Cap Trays. A bubble-cap tray is illustrated in Figure 5-7. The gas stream enters the liquid layer through holes or slots in the bubble caps mounted

on each tray. This type of unit can handle wide ranges of gas and liquid rates without adversely affecting efficiency because the bubble caps are liquid-tight.

Sieve Trays. Sieve trays contain a number of orifices ranging from 0.25 to 1 in. (0.64 to 2.5 cm) in diameter. Because of these relatively large openings, the sieve trays are less prone to solids accumulation and pluggage than other types of trays that have smaller orifices.

Figure 5-7 provides a more detailed picture of gas-liquid contact in bubble cap trays. The liquid flow direction in the bubble cap tray is as described above, i.e., across the tray. However, the geometry of the sieve tray shown in Figure 5-8 is the disk-and-donut arrangement. A central downcomer is used to provide radial liquid flow from the center outward, and then from the outer edge to the center in successive trays. Sieve trays may also be operated with liquid flow across each tray in alternating directions, much like the bubble-cap liquid flow.

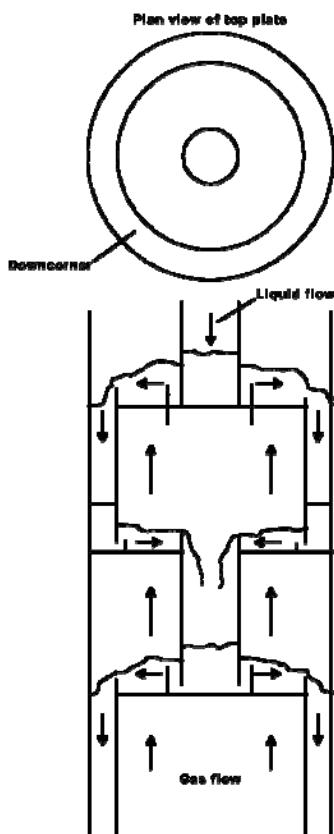


Figure 5-8. Gas-liquid contact in a disk-and-donut sieve tray.

Impingement Trays. The gas stream passes through small orifices in the impingement tray that are usually 3/16 in. (0.48 cm) in diameter. Small impingement targets above each orifice are used to promote gas-liquid contact immediately above the tray. Mass transfer is enhanced since a portion of the liquid is actually atomized due to the high gas velocities created by the small orifices and impingement targets. The liquid layer across the impingement tray is

maintained at 0.75 to 1.5 in. (1.9 to 3.8 cm) by means of an overflow weir on the discharge side of the tray. Impingement trays are somewhat more prone to plugging by solids present in the feed gas because of the smaller orifices.

Float Valve™ Trays. The gas stream flows up through small holes in the tray and lifts metal valves or caps that cover the openings. The valves are restrained by legs that limit vertical movement. The liftable caps act as variable orifices and adjust the size of the opening depending on gas flow rate through the absorber.

High removal efficiencies are possible in all properly designed tray towers because of the good gas-liquor contact that can be achieved on a tray. The use of several trays in series also ensures that gas-liquid maldistribution on a single tray does not severely limit the efficiency of the overall absorber.

Venturi and Ejector Absorbers

Venturi absorbers are used primarily when there is a need to simultaneously remove particulate matter and absorb gaseous contaminants. Ejector absorbers are used primarily in small-scale systems where it is uneconomical to provide a fan for gas movement. The gas stream flows through the absorber simply by the aspiration (suction) effect of the high-velocity ejector liquid stream. The ejectors function in a manner similar to aspirators on laboratory sinks. Ejector absorbers are also used in series arrangements for the concentration of acids in manufacturing processes.

Venturis. A typical venturi configuration, shown in Figure 5-9, consists of a converging section for the acceleration of the approaching gas stream containing the contaminant, a means to introduce the liquid absorbent stream, a gas-liquid contacting throat, and a diverging section for decelerating the gas stream and atomized liquid droplets.

Some venturis have a baffle-type adjustable throat mechanism that permits the velocity of the gas stream passing through the throat to be adjusted. This enables the unit to maintain conditions favorable for particle impaction, despite changes in the gas flow at different process operating rates. There are many different commercial designs of adjustable throat mechanisms.

Venturi absorbers normally operate with high gas-phase static pressure drops ranging from 10 to 100 in. W.C. (2.5 to 25 kPa). The necessary pressure drop is based primarily on the particle size distribution of the incoming gas stream and the applicable particulate matter removal requirements and is not directly related to the capability of the venturi to absorb gaseous contaminants.

In the throat, gas velocities can vary between 100 and 600 ft/sec (30 to 180 m/sec). These high velocities effectively create large interfacial surface area by atomizing the liquid. There is very limited time for gas absorption. In fact, at normal venturi throat velocities, the gas stream and the liquid droplets are in close contact for time periods of less than 0.002 seconds. There is a strong tendency for droplets to be entrained because of their small size. For this reason, both the gas and liquid exit through a cyclonic mist eliminator, where centrifugal force causes the small droplets to separate by migrating to the wall of the vessel.

The cyclonic mist eliminator is then followed by a standard mist eliminator at the top of the vessel.

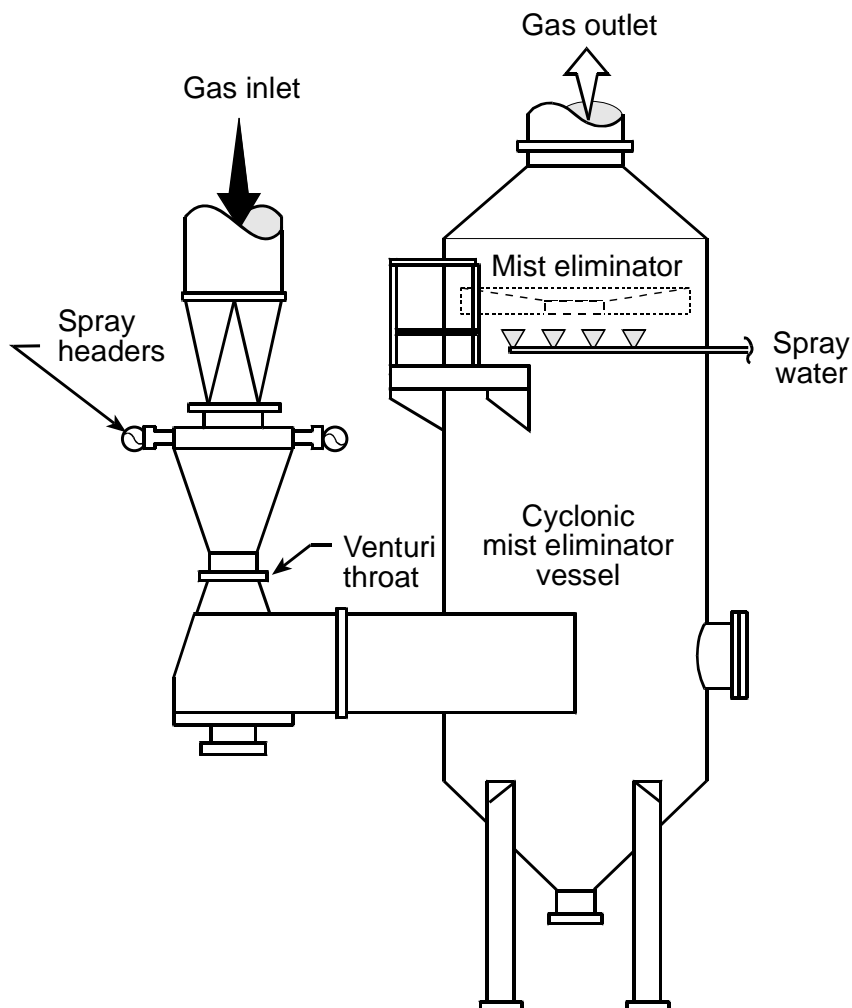


Figure 5-9. Venturi absorber.

To overcome the short residence time, some venturi systems used primarily for gaseous absorption operate at high (L/G) ratios ranging from 20 to 100 gallons per 1000 ACF (2.7 to 13 liters per m³ of gas). For comparison purposes, it should be noted that venturi (L/G) ratios for particulate matter removal are usually optimal in the range of 4 to 20 gallons per 1000 ACFM (0.5 to 2.7 liters per m³).

Ejector Absorbers. Ejector absorbers are often used in series as shown in Figure 5-10, where three ejector absorbers are followed by a packed-bed absorber. Solvent-laden gas is introduced near the top of the first ejector absorber and passes through the remaining ejector absorbers in series, and finally enters the packed-tower absorber for final polishing. The treated gas from the top of the packed-bed absorber is emitted to the atmosphere. Make-up absorbing

liquid is introduced into the packed bed and then passes from ejector to ejector in a direction opposite to that of the gas flow. This overall counterflow arrangement results in the most concentrated liquid contacting the most concentrated gas in the first ejector and fresh liquid contacting the least concentrated gas in the packed bed. “Product” liquid is removed from the system from the first ejector absorber stage.

Liquid is added to each ejector through a high-pressure spray nozzle operating at more than 80 psig aimed at the throat section of the ejector. This creates an aspiration effect that pulls the gas stream through each vessel and eliminates the need for a fan or blower to move the gas stream. The high-pressure sprays also form very small liquid droplets that provide a large gas-liquid interfacial area for absorption of gases. Mass transfer is aided by the highly turbulent conditions around the droplets, but is limited by the relatively short contact time between the droplets and the gas stream.

Ejector absorbers operate at high liquid-to-gas ratios (around 100 gallons/1000 ACF). The gas-phase static pressure rises (pressure increases in absorber) usually range between 4 and 8 in. W.C. (1 to 2 kPa). However, the overall power consumption is high because of the liquid pumping requirements.

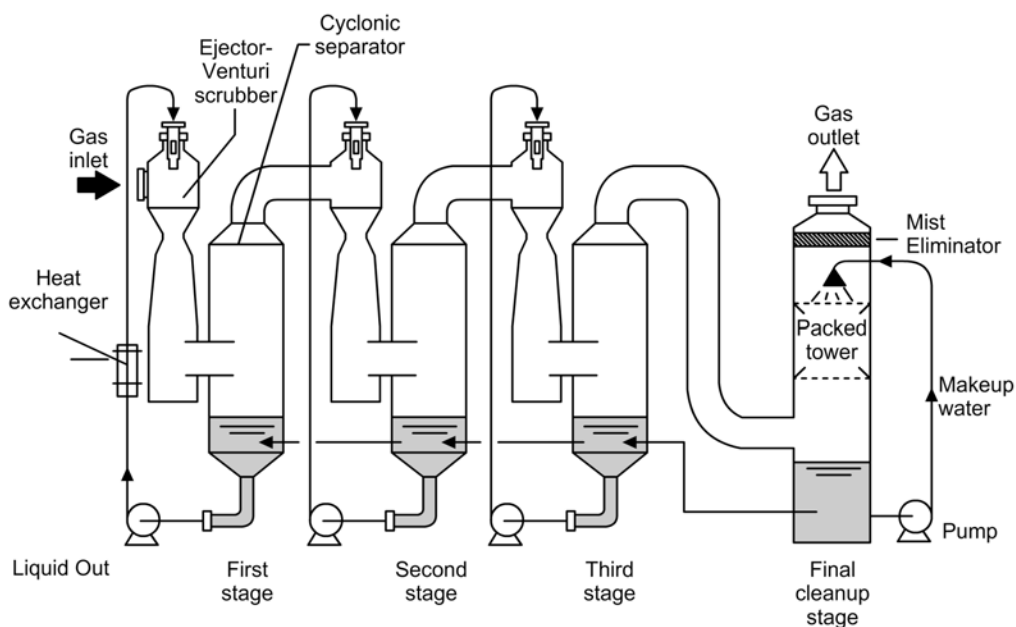


Figure 5-10. Ejector absorber.

Ejector absorbers are used in acid production facilities and also for some types of emergency scrubbers. Emergency scrubbers are often required in enclosed areas in the event of an accidental release of compressed gases such as ammonia or chlorine.

Biofiltration Beds

Biofiltration systems use aerobic microorganisms in a packed bed to consume organic compounds. The microorganisms are present in a thin layer over porous support packing composed of soil, compost, peat, or vegetation wastes. A simplified flowchart of a biofiltration system is shown in Figure 5-11.

The inlet gas stream must be humidified to approximately 95% relative humidity in order to avoid drying the bed and killing the microorganisms.² Water may be sprayed on the top of the bed in order to maintain total moisture levels equivalent to 40% to 60% of the total weight.² A portion of this water drains from the bed and is recirculated to minimize make-up water requirements and reduce wastewater discharge quantities.

The bed temperature must be maintained between approximately 68°F and 105°F (20°C and 40°C).^{3,4} High-temperature excursions can kill the organisms while low-temperature operations can suppress the biological activity. For cold weather operations, it is necessary to supply supplemental heat or to design the unit for the low levels of biological activity that exist at these temperatures.

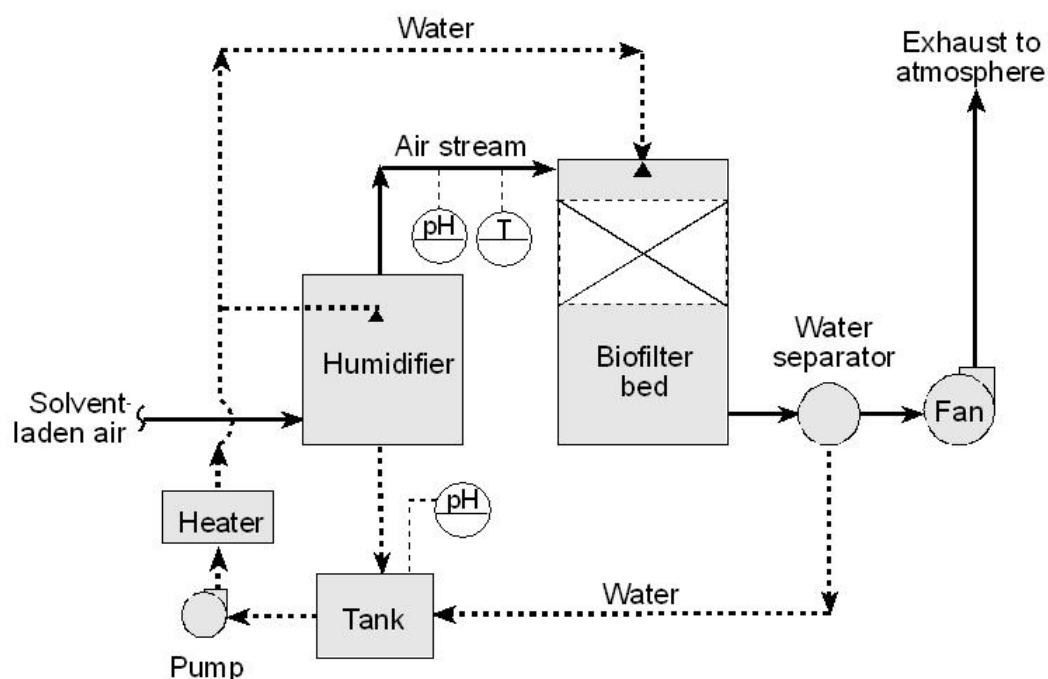


Figure 5-11. Biological oxidation system.⁵

The organic vapor contaminants passing through the bed must be soluble in order to enter the water layers surrounding the packing material. Once in the

water layers, the compounds must be biodegradable. The highly variable rates at which organic compounds are consumed must be taken into account when sizing the unit.

Sulfur- and nitrogen-containing organic compounds can generate acidic compounds during biodegradation. Alkali additives may be necessary to maintain the pH level in the range of 6 to 8 where the organisms are viable.²

The packed beds are usually approximately 3 feet (0.9 m) in height and have gas-flow static pressure drops between 4 and 12 in. W.C. (1 and 4 kPa).^{2,3,4} The pressure drop may increase over time because of the gradual compaction of the bed and the buildup of mineral matter within the bed. The beds must be replaced on a two- to five-year cycle.

Biological oxidation systems are used primarily for low concentration (< 500 ppm) organic vapor streams. They can tolerate short-term spikes of relatively high concentrations and periods when the process is not operational.

Components Common to Most Absorption Systems

Mist Eliminators

Most absorption systems generate liquid droplets that tend to be entrained in the gas stream leaving the treatment area. The mist eliminator is used to remove these entrained droplets prior to entering the induced draft fan (if present) and prior to discharge of the effluent from the stack. The droplets and the suspended and dissolved solids within the droplets emitted from the stack can create nuisance damage in the immediate vicinity.

The droplet sizes generated in absorbers range from approximately 200 to 1000 micrometers. While larger droplets quickly settle out of the gas stream, the small droplets are easily entrained and must be removed by means of impaction or centrifugal collection. Common types of mist eliminators used on absorbers include cyclonic vessels (Figure 5-9), chevrons (Figure 5-12), radial vanes (Figure 5-13), and mesh pads (Figure 5-14).

The cyclonic vessels have a tangential inlet and operate much like a conventional large-diameter cyclone used for particulate removal. Droplets are accelerated toward the vessel wall by centrifugal forces imparted by the spinning gas. Depending on the gas velocity, the gas stream spins one-half to two revolutions prior to discharge. They have reasonable efficiencies when operated close to the design inlet gas velocities; however, droplet removal decreases rapidly at very low or very high gas velocities. Because of the spinning action of the gas stream, it is often necessary to install anti-vortex baffles in the stack in order to eliminate cyclonic flow conditions at emission testing locations.

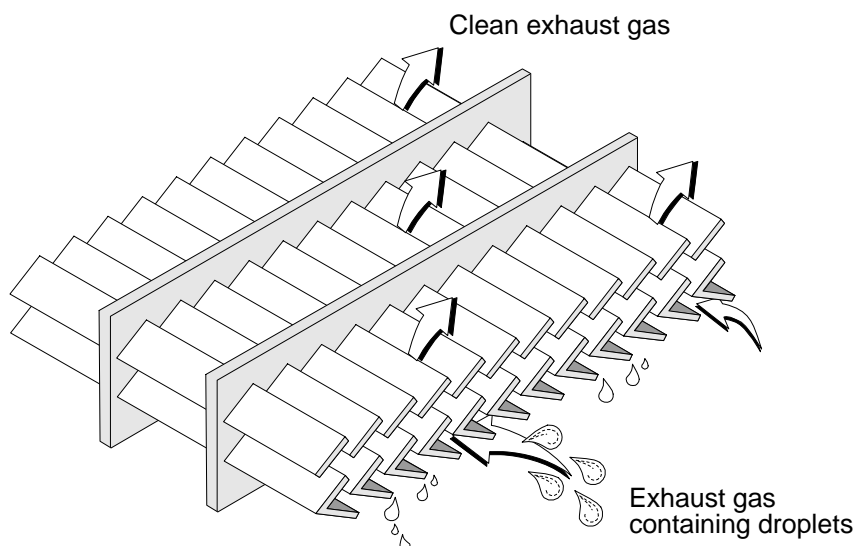


Figure 5-12. Chevron mist eliminator.

Chevrons are simply zig-zag baffles that force the gas to turn sharply several times while passing through the mist eliminator. Water droplets collect on the chevron blades and coalesce into larger droplets that fall downward into the absorber. Chevron mist eliminators are generally limited to gas velocities of less than approximately 20 ft/sec (6 m/sec). At higher velocities, liquid on the blades can be driven toward the outlet side of the chevron, where it can be reentrained in the gas stream. High velocities are usually caused by the unintentional build-up of solids on part of the chevron. This increases the velocity in the portion of the mist eliminator still open for flow. In order to minimize solids accumulation, clean water spray headers are placed on the inlet and/or outlet sides. These are activated intermittently on a once-per-shift or once-per-day basis, depending on the severity of the solids buildup problem.

Radial-vane mist eliminators, shown in Figure 5-13, are conceptually similar to chevrons. The droplet-laden gas stream is forced through a set of turning vanes at the top of the absorption vessel. Impaction of droplets occurs on the vanes as the gas stream turns to pass through the mist eliminator. A set of sprays is used to clean the vanes on an intermittent basis.

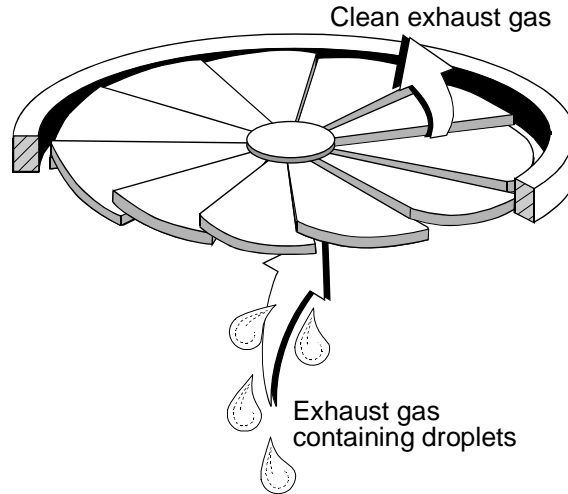


Figure 5-13. Radial-vane mist eliminator.

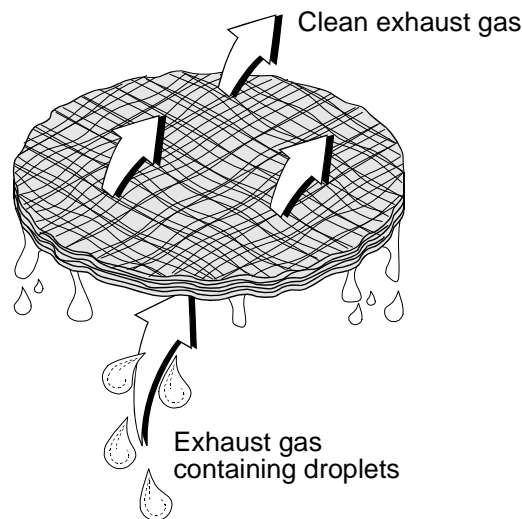


Figure 5-14. Mesh-pad mist eliminator.

Mesh pads are formed from woven or randomly interlaced metal or plastic fibers that serve as impaction targets. The pads can be up to 6 inches thick. As with the chevrons, there is a maximum gas velocity above which reentrainment is possible. This maximum gas velocity, which depends on the density of the mesh (usually 5–9 lb_m/ft³), on the materials of construction, and on the gas density, is usually in the range of 12 ft/sec (3.7 m/sec).

Mesh pads are often layered, with the inlet layers capable of removing large quantities of large diameter droplets without overloading. The middle- and outlet-side layers are more compact and have high removal efficiencies for smaller liquid droplets. These units have maximum velocities of 8 to 15 ft/sec (2.4 to 4.6 m/sec), depending on the pad construction characteristics. Mesh-pad

mist eliminators usually have clean water spray systems to remove solids. Blinding of these mist eliminators can lead to excessive pressure drops and liquid reentrainment.

Normal static pressure drops across mist eliminators range from 0.5 to more than 4 in. W.C. (0.13 to 1.0 kPa). Static pressure drop gauges are useful for monitoring the pressure drop and providing an early warning of solids accumulation.

Pumps and Piping Systems

Centrifugal pumps are commonly used for absorber systems. In these pumps, the liquid enters axially and is accelerated by the rotating impeller. As the liquid leaves the impeller radially, the liquid velocity decreases and the pressure increases.

The piping system generally consists of a number of components, including the suction pipe, strainer, suction-side check valve, and discharge control valve. The strainer is used for removal of small bits of metal and other contaminants that can be caught in the liquid stream. The suction-side check valve is used to reduce the risk of air infiltration into the suction-side piping during an outage of the system. The discharge valve is used to adjust liquid flow from the pump.

Instrumentation

Instruments are used throughout the absorber system to protect components and to monitor performance. A partial list of the parameters and common monitoring locations for most systems include the following:

Gas Temperature

- Absorber inlet
- Absorber outlet

Liquid Flow Rate

- Recirculation liquid stream
- Purge liquid stream

Liquid Pressure

- Recirculation pump discharge
- Absorber liquid distribution headers

Liquid pH

- Recirculation liquid tank
- Recirculation liquid stream

Static Pressure Drop

- Absorber vessel
- Mist eliminator

The absorber inlet temperature gauge is used to detect high gas temperatures that would impair absorption efficiency and could damage the absorber system. Many absorbers are constructed of fiberglass-reinforced plastics (FRP) or have corrosion-resistant liners that have maximum temperature limits ranging from 200°F to 400°F (90°C to 200°C). In the event of high inlet gas temperature, emergency flush systems may be included to protect the system during an emergency shutdown.

The outlet gas temperature gauge is useful for evaluating absorber performance and to protect the downstream fan. Loss of scrubbing liquid flow because of pump failure, pipe freezing, pipe breakage, or pipe blockage could result in higher-than-desirable gas temperatures.

Liquid flow monitors, which are used to ensure that the flow rates remain within the intended operating range, are often required by both U.S. EPA and state regulations. They are especially important on systems that do not add alkali or other additives to react with the pollutants absorbed in the system. In these cases, the liquid flow must be maintained at a rate above the solubility limits for the pollutants being removed from the gas stream. The type of liquid flow monitor used depends on the size of the facility and the characteristics of the liquid being monitored. Relatively clean liquid streams can be monitored by orifice meters, swinging vane meters, and rotameters. Magnetic flow meters and ultrasonic meters can be used on streams with moderate solids levels.

Liquid pressure gauges are used on supply headers to the absorber to monitor for problems such as nozzle pluggage, nozzle orifice erosion, and header pluggage. Pluggage problems are indicated by higher than normal pressures.

Most liquid pressure gauges are direct-indicating-type instruments. pH instruments are used to control the alkaline feed rate to absorber systems (acid gas removal applications). It is usually advantageous to maintain the pH at levels between 5 and 9. At low pH, the materials are vulnerable to corrosion. At high levels, calcium and magnesium compounds can precipitate out of solution and create scale in piping, nozzles, scrubber walls, and mist eliminators.

The static pressure gauge across the absorber vessel is used primarily to evaluate routine performance. In large units, the static pressure is sensed by a differential pressure transmitter, and an electrical signal is sent to a monitoring system in the control room. Direct-indicating gauges such as manometers and Magnehelic® gauges are used in many smaller systems.

Static pressure-drop gauges are used on mist eliminators to monitor for excessive solids build-up that could lead to droplet reentrainment and fan operating problems, and to indicate the need to activate the cleaning sprays.

5.2 Operating Principles

The purpose of this section is to introduce important variables that influence the gaseous pollutant-removal efficiency of absorbers. These operating principles apply to essentially all types of absorbers discussed previously.

Mechanisms of Absorption

Two-Film Theory

The two-film theory of absorption is illustrated in Figure 5-15. All resistance to mass transfer is assumed to be associated with a thin gas film and a thin liquid film immediately adjacent to the gas-liquid interface. The gaseous contaminant, component A, with mole fraction y_A , is transported by turbulent mixing action to the boundary of the gas film. The contaminant then diffuses through the gas film to the interface where the mole fraction is y_{Ai} . The interface is assumed to be at equilibrium and the mole fraction at the liquid interface is x_{Ai} . From the interface, component A then diffuses across the liquid film to the bulk liquid where the mole fraction is x_A . The discontinuity between y_{Ai} and x_{Ai} is due to the composition difference between the gas and liquid.

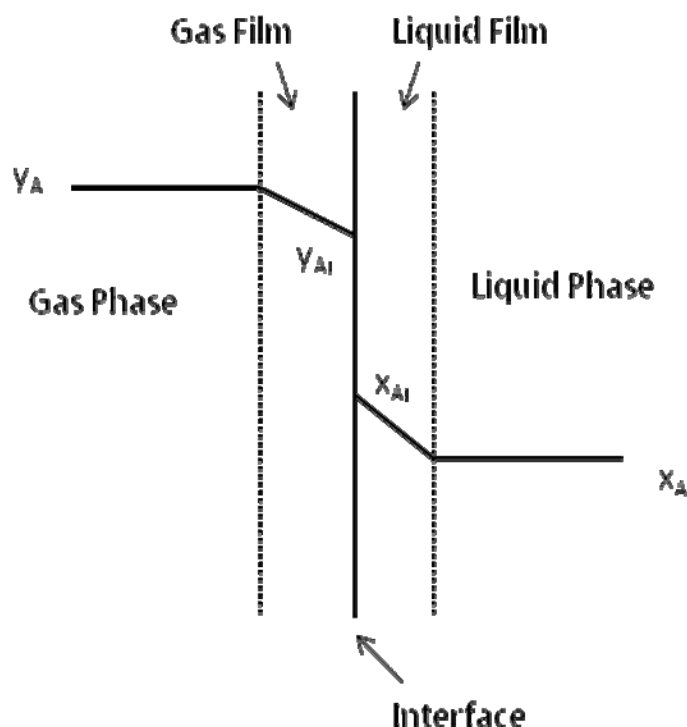


Figure 5-15. Two-film theory of absorption.

When the mole fraction of A in the liquid reaches its saturation limit, the rates of mass transfer are equal in both directions. The two phases are in equilibrium and no additional contaminant removal is possible. Accordingly, it is important to design and operate absorbers so that saturation conditions are not reached. There are two ways to achieve this goal.

- Provide sufficient liquid so that the dissolved contaminants do not reach their solubility limit.

- Chemically react the dissolved contaminants so that they cannot return to the gas phase.

In this chapter we are interested in dissolution without chemical reaction. Absorption with reaction is treated in a later chapter.

Solubility

The solubility of a gas in a liquid is a function of the temperature and partial pressure of the contaminant in the gas phase. Gas phase total pressure can also influence solubility, but this is not a major variable in absorbers used for air pollution control since they operate near atmospheric pressure.

Solubility data for the ammonia-water system are presented in Table 5-1 as a function of temperature. Ammonia concentration in the gas phase is expressed as partial pressure in units of mm Hg, while liquid phase ammonia concentration is expressed in weight of NH_3 per 100 weights of H_2O . The data are taken from Perry's *Chemical Engineers Handbook*.⁸

Table 5-1. Equilibrium Partial pressure of ammonia over aqueous solutions, mm Hg.							
Wt. NH_3 per 100 wts. H_2O	0°C	10°C	20°C	30°C	40°C	50°C	60°C
20.0	64	103.5	166	260	395	596	834
15.0	42.7	70.1	114	179	273	405	583
10.0	25.1	41.8	69.6	110	167	247	361
7.5	17.7	29.9	50	79.7	120	179	261
5.0	11.2	19.1	31.7	51	76.5	115	165
4.0		16.1	24.9	40.1	60.8	91.1	129.2
3.0		11.3	18.2	29.6	45	67.1	94.3
2.5			15.0	24.4			77.0
2.0			12.0	19.3			61.0
1.6				15.3			48.7
1.2				11.5			36.3
1.0							30.2
0.5							

The most common method of analyzing solubility data is to use an equilibrium diagram. This is a plot of the mole fraction of solute (contaminant) in the liquid phase, denoted as x , versus the mole fraction of solute in the gas phase, denoted as y . Equilibrium data for the $\text{NH}_3\text{-H}_2\text{O}$ system given in Table 5-1 are plotted in Figure 5-16 at 0°C , 20°C and 40°C .

Figure 5-16 illustrates the temperature dependence of the absorption process. At a constant mole fraction of solute in the gas (y), the mole fraction of SO_2 in the liquid (x) increases as the liquid temperature decreases.

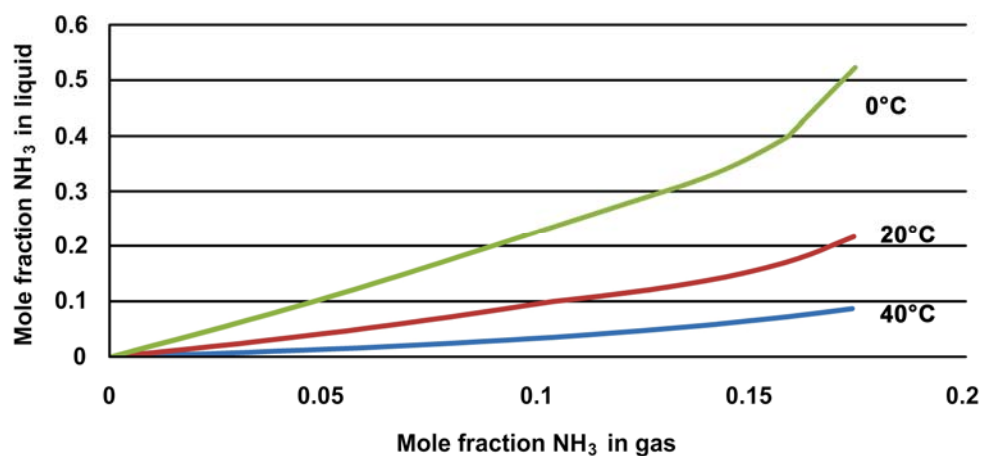


Figure 5-16. NH_3 -water system.

Henry's Law

Under certain conditions, the relationship between the gas phase concentration and the liquid phase concentration of the contaminant at equilibrium can be expressed by Henry's Law.

$$\text{(Eq. 5-1)} \quad p_A = H_p x_A$$

Where:

- p_A = partial pressure of contaminant in gas phase at equilibrium
- H_p = Henry's Law constant when the gas concentration is expressed in partial pressure
- x_A = mole fraction of contaminant dissolved in the liquid phase at equilibrium

Henry's Law can be written in an alternate form that is consistent with the data in Figure 5-17 by dividing both sides of Equation 5-1 by the total pressure, P , of the system. The left side of the equation becomes the partial pressure divided by the total pressure, which is equal to the mole fraction in the gas phase, y_A . The new value of Henry's constant H_y is simply the old value H_p divided by the total pressure P . It is important to express the contaminant concentrations in mole fraction as indicated in Equation 5-2.

(Eq. 5-2) $y_A = H_y x_A$

Where: y_A = mole fraction of the contaminant in the gas phase at equilibrium

H_y = Henry's Law constant when the gas concentration is expressed in mole fraction

x_A = mole fraction of contaminant dissolved in the liquid phase at equilibrium

(Note: H is now dependent on the total pressure.)

Equation 5-2 is the equation of a straight line where the slope (m) is equal to H_y . Thus, Henry's Law can be used to predict solubility when the equilibrium line is straight. This is often the case when the contaminant concentration is very small, as in many air pollution control applications. For example, Figure 5-17 shows that the equilibrium line is approximately straight to gas phase mole fractions of NH_3 to about 0.15.

Another restriction on using Henry's Law is that it does not hold true for gases that react or dissociate upon dissolution. If this happens, the gas no longer exists as a simple molecule. For example, scrubbing HF or HCl gases with water causes both compounds to dissociate in solution. In these cases, the equilibrium lines are curved rather than straight. Data on systems that exhibit curved equilibrium lines must be obtained from experiments.

Problem 5-1

Use the $\text{NH}_3\text{-H}_2\text{O}$ data in Table 5-1 to show that Henry's Law is valid at low concentrations of NH_3 and calculate H_p and H_y at 20°C in this low concentration range.

Solution:

Step 1. From Equation 5-1, $H_p = P_A/x_A$. The mass concentration data from Figure 5-1 must be converted to x_A , the mole fraction of NH_3 in the liquid.

$$x_A = (\text{moles A})/(\text{moles A} + \text{moles H}_2\text{O}) \\ = (m_A/M_A)/[(m_A/M_A) + (m_{\text{H}_2\text{O}}/M_{\text{H}_2\text{O}})]$$

Use the first data entry from Table 5-1 as an example:

$$m_A = 20, m_{\text{H}_2\text{O}} = 100, M_A = 17, \text{ and } M_{\text{H}_2\text{O}} = 18$$

$$x_A = (20/17)/[(20/17) + (100/18)] = 0.175$$

Step 2. Converting the remaining mass concentration data in the same manner leads to the following table of $x_A - P_A - H_p$.

x_A	P_A	H_p
0.175	166	949
0.137	114	832

0.095	69.6	732
0.0735	50	680
0.0503	31.7	630
0.0401	24.9	621
0.0301	18.2	605
0.0258	15.0	581
0.0208	12.0	576

It is clear from examining the values of H_p that Henry's Law is not valid over the entire concentration range. However, this is not surprising since Henry's Law is known to be valid only at low concentrations. The last three entries, for x_A less than 0.0301, are effectively constant at an average value of $H_p = 587$. This value can be accepted to be approximately correct at low concentrations.

Step 3. In deriving Equation 5-2:

$$H_y = H_p/P$$

$$H_y = 587/760$$

$$H_y = 0.772$$

The final values with units are:

$$H_p = 587 \text{ mm Hg/mole fraction NH}_3 \text{ in liquid}$$

$$H_y = 0.772 \text{ mole fraction NH}_3 \text{ in gas/mole fraction NH}_3 \text{ in liquid}$$

5.3 Capability and Sizing

This section concerns the evaluation of new absorber systems. The primary issues are (1) the ability of the scrubbing system to achieve efficient gaseous pollutant removal and (2) the adequacy of the mist eliminator to remove entrained droplets.

Gaseous Pollutant Removal Capability

There are two general approaches to evaluating the capability of an absorber system: (1) empirical evaluations based on previously installed units on similar sources and (2) pilot scale tests.

Empirical Model Approach

Most absorber manufacturers have extensive databases describing the performance of their commercial absorbers and the common types of packing materials. These data provide a starting point in determining if a given type of absorber will be able to meet the performance requirements specified by the purchaser. Site-specific information is considered along with this historical

performance data to determine if an absorber would be appropriate. The most important site-specific data to be considered are listed below.

- Gas flow rates (average and maximum)
- Types of gaseous pollutants present
- Concentrations of the gaseous pollutants
- Removal efficiency requirements
- Make-up water availability
- Purge liquid flow limitations
- Inlet gas temperatures (average and maximum)
- Particulate matter loadings
- Operating schedule

These data can also be used to determine the absorber liquid-to-gas ratio, the alkali requirement (if needed), the make-up liquid and purge liquid flow rates, and the basic sizing parameters, such as the absorber diameter and absorber height.

Most absorber manufacturers have incorporated the empirical data from prior installations into mass transfer rate models. These models calculate (1) the liquid-to-gas ratios required at the minimum and average gas temperatures, (2) the number of beds or trays needed for the required removal efficiency, and (3) the diameter of the absorber based on the liquid-to-gas ratio and the maximum gas flow rate.

The advantage of the empirical/mass transfer rate model approach is that most absorber manufacturers have an extensive database concerning the mass transfer and overall performance capability of absorbers for similar applications. The primary disadvantage of this approach is that occasionally the data provided to the manufacturers may be inaccurate or incomplete. For example, the intermittent process operating conditions of some sources can generate high particulate matter loadings that could plug a packed bed or an impingement tray scrubber. In other cases, the estimated gas flow rate for a new process is less than the actual gas flow rate from the operating system. Some types of absorbers cannot maintain high removal efficiencies at gas flow rates significantly above or below the design levels. Accordingly, the success of the empirical approach depends, in part, on the completeness and accuracy of the source descriptive data provided to the absorber designer.

Pilot-Scale Tests

Pilot-scale performance tests can be conducted when there is uncertainty concerning the applicability of an absorber or the necessary size of an absorber. These tests are preferably conducted on the specific source to be controlled so that the characteristics of the gas stream are inherently taken into account. If this is an entirely new application that has not yet been built, a similar existing unit can be tested.

The tests are normally conducted using a small skid-mounted absorber system capable of handling 100 to 1000 ACFM (2.8 to 28 m³/min). The gas is pulled from the effluent duct from the process source. The performance of the

pilot-scale scrubber system is usually determined using conventional U.S. EPA reference method air emission tests.

The primary advantage of pilot-scale tests is that the performance of an absorber very similar to the proposed unit can be evaluated on the actual gas stream. Site-specific problems, such as the presence of sticky particulate matter, short-term spikes in the gaseous pollutant concentration (e.g., reactor charging), and severe temperature variations, can be taken into account. Furthermore, a test can be conducted to identify the optimal operating conditions. These tests include the liquid-to-gas ratio, the recirculation liquor pH, and the recirculation liquid purge rate. The main disadvantage is that pilot-scale tests are both time-consuming and expensive. Also, pilot-scale tests usually indicate slightly higher pollutant-removal efficiencies than can be achieved by the full-scale system, because a variety of non-ideal gas flow conditions are more significant on the larger systems.

Absorber Sizing

Liquid-to-Gas Ratios

The liquid-to-gas ratio (L/G) is defined as the quantity of liquid fed to the absorber divided by the outlet gas flow rate, often expressed in units of gallons per 1000 ACF. This definition is illustrated in Figure 5-17.

The liquid-to-gas ratio is important for two reasons: (1) there must be sufficient liquid to avoid mass transfer equilibrium, and (2) there must be good gas-liquid contact within the absorber. The combinations of factors that influence gas-liquid contact are sometimes referred to as *hydraulic* factors.

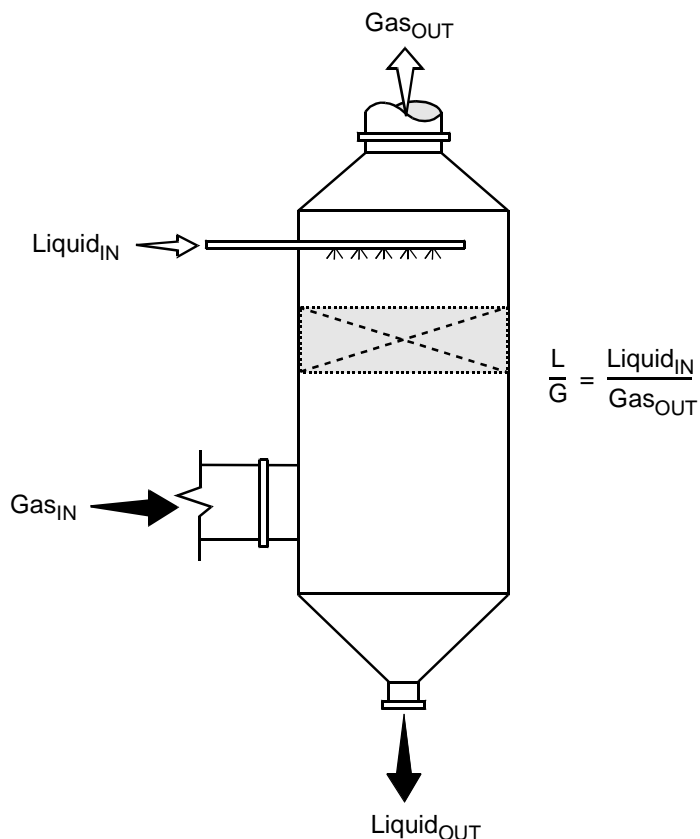


Figure 5-17. Definition of the liquid-to-gas ratio.

An estimate of the minimum required (L/G) can be obtained based on the solubility data of the contaminant and mass balance information. This procedure can be used for systems in which the contaminant is at relatively low concentrations, does not have a high heat of absorption, and does not react in solution.

Material Balance Calculations of Minimum Liquid-to-Gas Ratio

Figure 5-18 illustrates a typical counter-current flow absorber. For convenience, the top and bottom of the column are indicated by the subscripts 1 and 2, respectively.

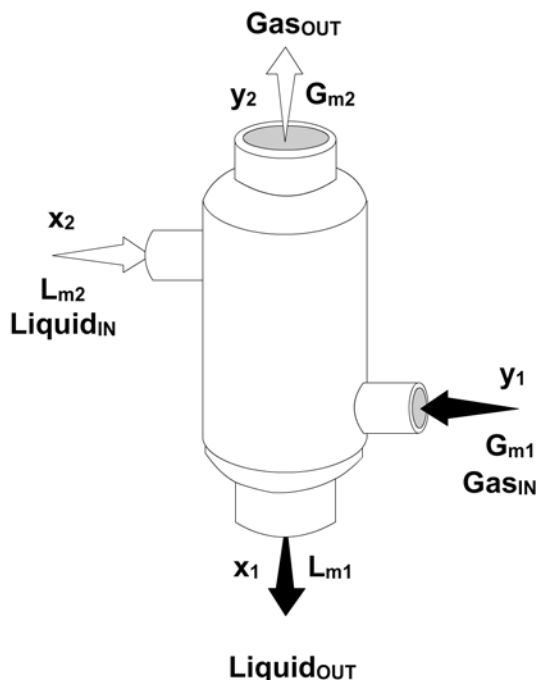


Figure 5-18. Material balance for countercurrent-flow absorber.

The following material balance equation equates the moles of contaminant entering in streams G_{m1} and L_{m2} to the moles leaving in streams G_{m2} and L_{m1} .

(Eq. 5-3)
$$G_{m1}y_1 + L_{m2}x_2 = G_{m2}y_2 + L_{m1}x_1$$

Where:

- G_m = total gas molar flow rate (gm moles/hr)
- y = mole fraction of contaminant in gas stream
- L_m = total liquid molar flow rate (gm moles/hr)
- x = mole fraction of the contaminant in pure liquid

It turns out to be convenient to write the material balance equations on the basis of mole ratios instead of mole fractions. New concentration parameters, Y and X , are defined as follows.

(Eq. 5-4)
$$Y = \frac{\text{mole fraction contaminant in gas}}{\text{mole fraction contaminant - free gas}} = \frac{y}{1 - y}$$

(Eq. 5-5)
$$X = \frac{\text{mole fraction contaminant in liquid}}{\text{mole fraction contaminant - free liquid}} = \frac{x}{1 - x}$$

In air pollution control problems, the contaminant concentrations are usually small, i.e., y and x are generally small compared to 1. Under these conditions, $Y \approx y$, and $X \approx x$. This simplification is used in the following analysis. If the mole fraction of contaminant in the inlet gas is larger than a few percent by volume,

this assumption is invalid and will cause errors in the material balance calculations.

An overall (total mole) balance across the absorber in Figure 5-20 yields the following equation:

$$\text{(Eq. 5-6)} \quad G_{m1} + L_{m2} = G_{m2} + L_{m1}$$

Equation 5-3 is rewritten in terms of X and Y using the simplifications indicated in equations 5-4 and 5-5 to give:

$$\text{(Eq. 5-7)} \quad G_{m1} Y_1 + L_{m2} X_2 = G_{m2} Y_2 + L_{m1} X_1$$

Equation 5-7 can be further simplified by recognizing that as the gas and liquid streams flow through the absorber, their flow rate does not change appreciably. Therefore, it is not necessary to include the subscripts 1 and 2 on the total gas and liquid flow rates.

$$\text{(Eq. 5-8)} \quad G_{m1} = G_{m2} = G_m \quad \text{and} \quad L_{m1} = L_{m2} = L_m$$

The contaminant material balance now becomes:

$$\text{(Eq. 5-9)} \quad G_m(Y_1 - Y_2) = L_m(X_1 - X_2)$$

Rearranging Equation 5-9 yields Equation 5-10.

$$\text{(Eq. 5-10)} \quad Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2)$$

These simplifications can be justified by the following example. Consider a 10,000 SCFM exhaust gas stream containing 1000 ppm of contaminant. This is equivalent to a contaminant mole fraction of only 0.001 or 10 SCFM of contaminant. If the absorber removed all of the contaminant, the total gas flow rate would only change from 10,000 SCFM at the inlet to 9990 at the outlet. The transfer of a quantity this small is negligible in an overall material balance.

Equation 5-10 is the equation of a straight line, known as an operating line, on a Y-X diagram. The operating line is really nothing more than a graphical representation of the contaminant material balance. This line defines operating conditions within the absorber: the material going in and the material coming out represent the terminal points of the operating line. An typical equilibrium diagram and operating line are plotted on a Y-X diagram in Figure 5-19. The equilibrium line in this example is shown as curved, although in cases where Henry's Law is applicable, both the equilibrium and operating lines would be straight. The slope of the operating line is the ratio of the molar flow rates of liquid and gas. The driving force for mass transfer is graphically represented by the "distance" between the operating and equilibrium lines.

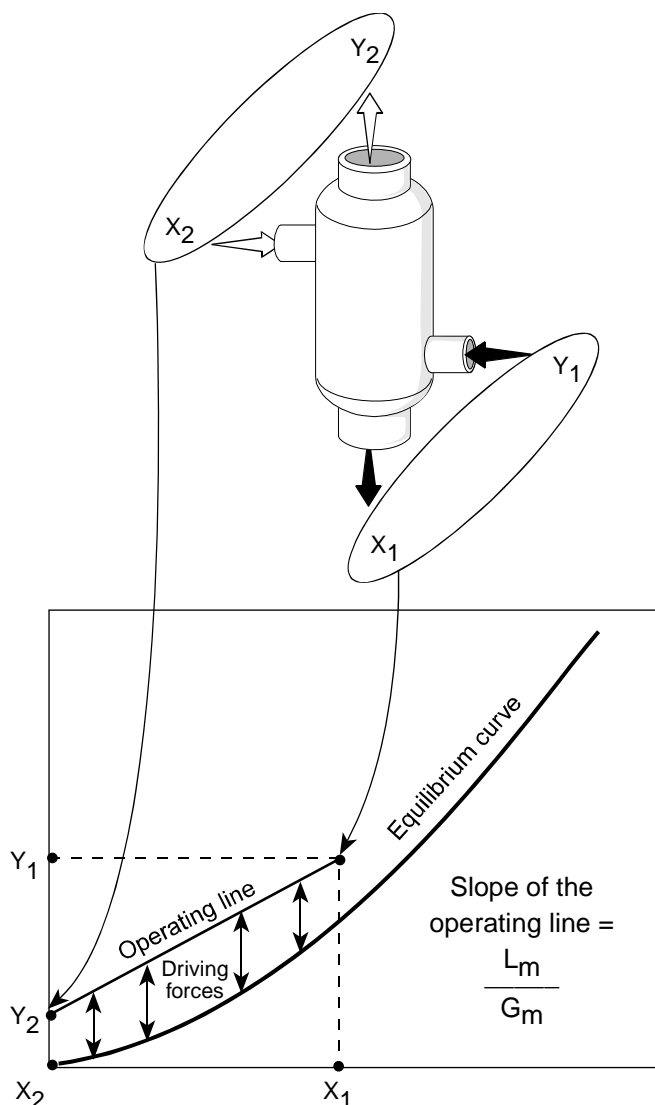


Figure 5-19. Y-X diagram showing the equilibrium and operating lines.

In the typical design problem, the quantity of gas to be treated (G_m) and the inlet contaminant concentration in the gas (Y_1) are set by process conditions. Air pollution emission limitations specify the outlet contaminant concentration (Y_2). The composition of the liquid into the absorber (X_2) is also generally known. If the inlet liquid contains no contaminant, the value of X_2 is zero. This is the situation shown in Figure 5-19. However, because of liquid recycle, the inlet liquid may contain some contaminant in which case X_2 will be somewhat greater than zero, but small. Thus, the coordinate positions Y_1 , Y_2 , and X_2 , along with G_m are known. The unknowns are X_1 and L_m .

Figure 5-20a is a typical equilibrium diagram with the known operating points Y_1 , Y_2 and X_2 designated for a countercurrent flow absorber. When the minimum liquid rate required to achieve the specified separation, the inlet gas concentration of contaminant (Y_1) is in equilibrium with the outlet liquid contaminant concentration, designated as X_{max} . Since the gas and liquid are in

equilibrium at these conditions, the coordinates of point Y_1, X_{\max} must lie on both the equilibrium and operating lines as represented by B.

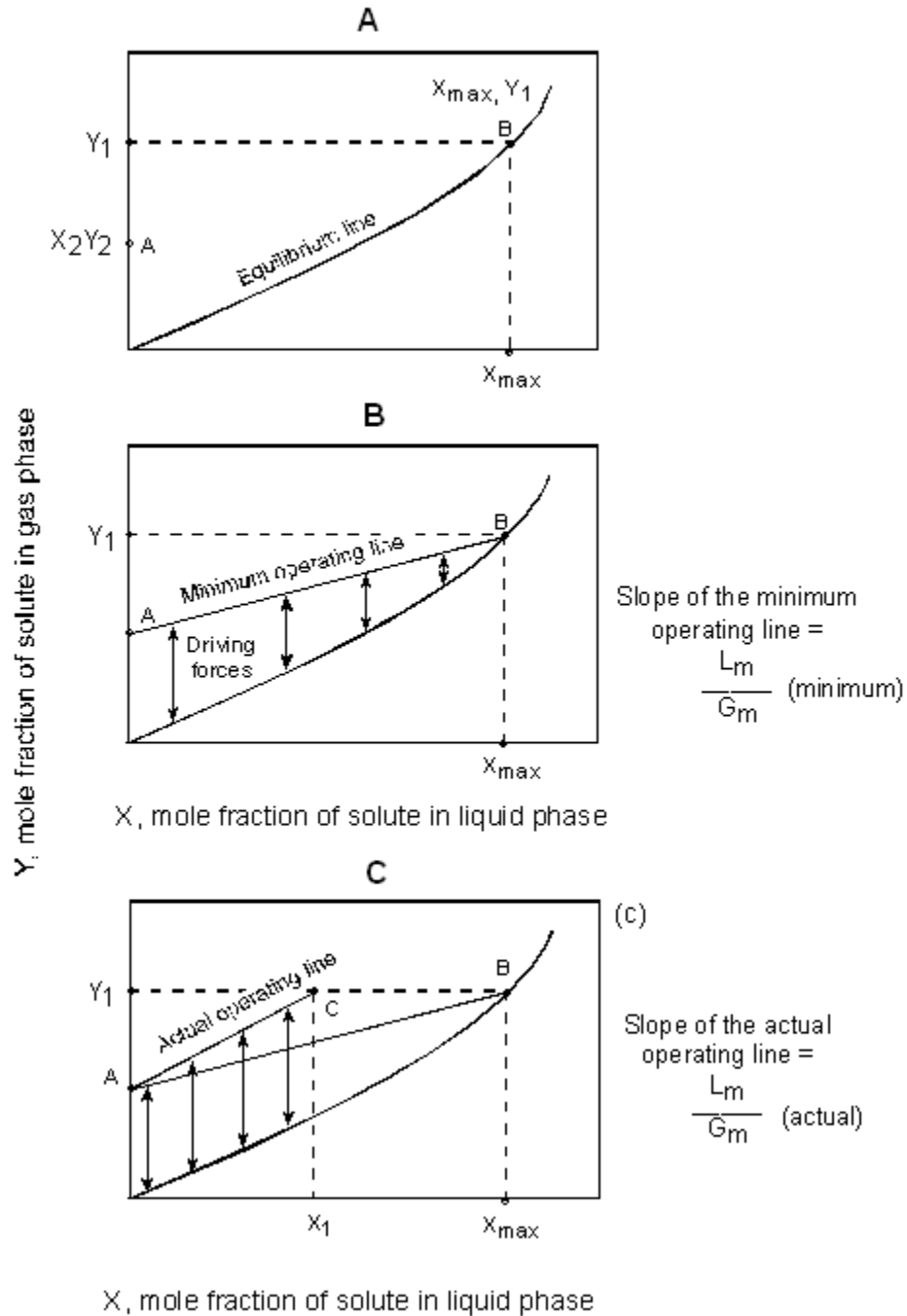


Figure 5-20. Liquid-to-gas ratio.

In Figure 5-20b, the slope of the line drawn between points A and B represents the operating conditions at minimum liquid flow rate. The driving force for mass transfer, which is represented by the distance between the equilibrium and operating lines, decreases to zero at point B. By knowing the

slope (L_m/G_m) of the minimum operating line, the minimum liquid rate can easily be determined by substituting the known gas flow rate. This procedure is illustrated in Problem 5-2.

Determining the minimum liquid flow rate (L_m/G_m) is important because absorbers are usually operated at some multiple, perhaps 25% to 100% greater than the minimum. A typical absorber might operate at a liquid rate 50% greater than the minimum (i.e., 1.5 times the minimum liquid-to-gas ratio). Line AC in Figure 5-20c is drawn at a slope of 1.5 times the minimum (L_m/G_m), and is referred to as the actual operating line.

Operating at the minimum (L_m/G_m) would require an infinitely large column, as the driving force for mass transfer is zero when the operating and equilibrium lines intersect. As the actual value of (L_m/G_m) increases above the minimum, the size of the absorber decreases. The smaller column results in a decrease in capital cost but an increase in operating cost because of the larger liquid flow rate. In the real situation there is an optimum (L_m/G_m) corresponding to minimum total cost. The optimum (L_m/G_m) is often near the value of $1.5(L_m/G_m)$ as described above. The following problem illustrates the calculation of (L_m/G_m).

Problem 5-2

Calculate $(L_m/G_m)_{\min}$ for the removal of 90% of the NH_3 from a $85.0 \text{ m}^3/\text{min}$ (3000 ACFM) feed gas containing 3% NH_3 and 97% air. The inlet liquid is pure H_2O and the temperature and pressure are 293 K and 1 atm , respectively. Use the results from Problem 5-1.

Solution:

Step 1. Sketch and label a drawing of the system. Figure 5-21 shows the pertinent parameters for this problem.

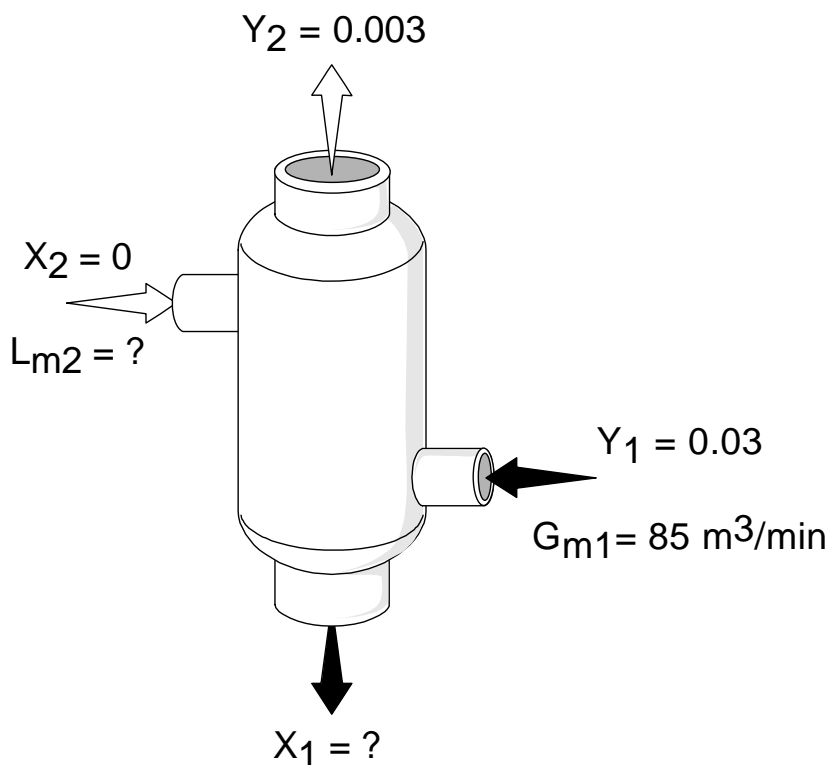


Figure 5-21. Absorber operating conditions in Problem 5-2.

Step 2. At the minimum, liquid rate Y_1 and X_1 will be in equilibrium. The liquid will be saturated with NH_3 .

$$Y_1 = H_y X_1 \quad (\text{Remember that } y_1 = Y_1 \text{ and } x_1 = X_1 \text{ for dilute system.})$$

$$H_y = 0.772 \frac{\text{mole fraction } \text{NH}_3 \text{ in air}}{\text{mole fraction } \text{NH}_3 \text{ in water}} \quad (\text{from Problem 5-1})$$

$$0.03 = 0.772 X_1$$

$$X_1 = 0.0389 \text{ mole fraction}$$

Step 3. $(L_m/G_m)_{\min}$ can be obtained directly by rearranging Equation 5-9.

$$Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2)$$

$$\left(\frac{L_m}{G_m}\right)_{\min} = \frac{Y_1 - Y_2}{X_1 - X_2}$$

$$\left(\frac{L_m}{G_m}\right)_{\min} = \frac{0.03 - 0.003}{0.0389 - 0}$$

$$(L_m/G_m)_{\min} = 0.694 \text{ g moles water/g moles air}$$

Step 4. Convert m^3 of air to gram moles; then compute the minimum required liquid flow rate. At 0°C and 101.3 kPa, there are $0.0224 \text{ m}^3/\text{g moles}$ ($359 \text{ ft}^3/\text{lb mole}$) of an ideal gas. At 20°C , $0.0244 \text{ m}^3/\text{g mole}$ ($293^\circ\text{K}/273^\circ\text{K}$) = $0.024 \text{ m}^3/\text{g mole}$ (EPA standard conditions).

$$\begin{aligned} G_m &= 85.0 \frac{\text{m}^3}{\text{min}} \left(\frac{\text{g mole}}{0.024 \text{ m}^3} \right) \\ &= 3,540 \frac{\text{g mole air}}{\text{min}} \end{aligned}$$

$$(L_m)_{\min} = [0.694 \text{ g moles water/g mole air}] G_m$$

$$(L_m)_{\min} = (0.694)(3540) = 2447 \text{ g mole water/min}$$

$$L_{\min} = (2447 \text{ g moles H}_2\text{O/min})(18 \text{ g/g mole H}_2\text{O})$$

$$= 44,227 \text{ g/min}$$

$$L_{\min} = 44,227 \text{ g/min} \left(\frac{1 \text{ lb}_m}{453.6 \text{ g}} \right) \left(\frac{1 \text{ ft}^3}{62.4 \text{ lb}_m} \right) \left(7.48 \frac{\text{gal}}{\text{ft}^3} \right)$$

$$L_{\min} = 11.7 \text{ gal/min}$$

Step 5. Figure 5-22 illustrates the graphical solution to this problem. Multiply the slope of the minimum operating line by 1.5 to get the slope of the actual operating line (line AC).

$$L = 1.5 L_{\min} = 1.5(2447 \text{ g mole/min}) = 3670 \text{ g mole/min, or}$$

$$= 1.5(44,227 \text{ g/min}) = 66,340 \text{ g/min, or}$$

$$= 1.5(11.7 \text{ gal/min}) = 17.6 \text{ gal/min}$$

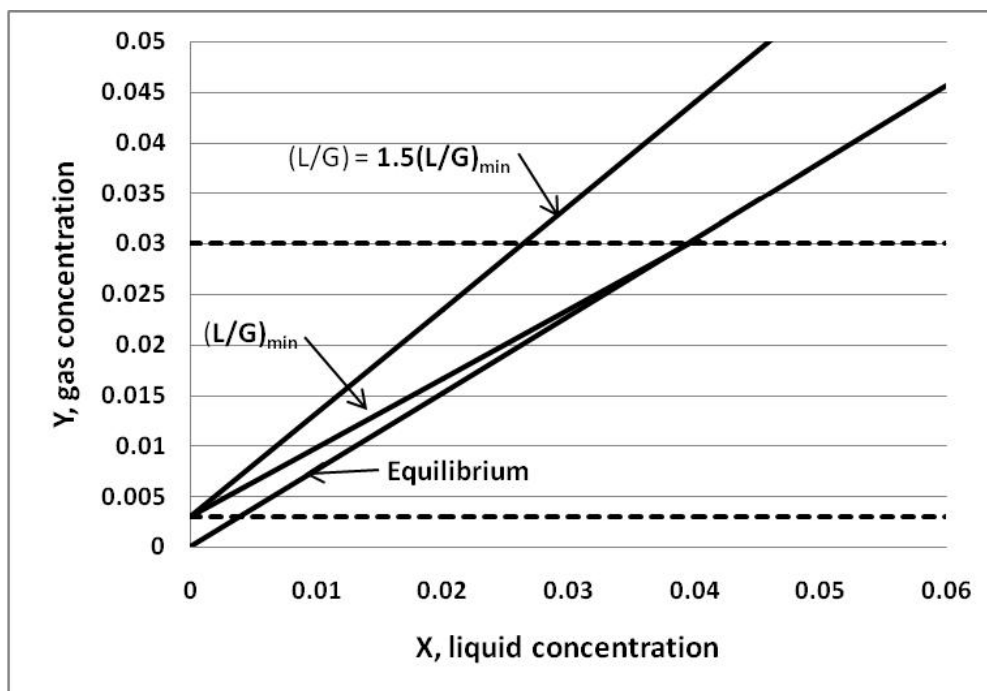


Figure 5-22. Graphical representation of NH_3 absorber problem (Problem 5-2).

The evaluation technique used in Problem 5-2 applies mainly to absorbers in which the contaminant is relatively dilute and does not react in solution. For absorbers that use alkali or other types of reagents that react with the dissolved materials, the liquid-to-gas ratio is determined based primarily on the hydraulic factors that affect gas-liquid distribution.

The relationship between the equilibrium line and the actual operating line used in the absorbers is termed the absorption factor (defined in Equation 5-11). This is simply the ratio of the slopes of the operating line and the equilibrium line.

$$\text{(Eq. 5-11)} \quad \text{AF} = \frac{L_2}{mG_1}$$

Where:

- AF = absorption factor
- L_2 = molar flow rate of liquid
- m = slope of the equilibrium line on a mole fraction basis = H_y
- G_1 = molar flow rate of gas

Packed-Tower Absorber Diameter and Height

The diameter and height of the bed(s) can be estimated for packed-tower absorbers. The starting point in these calculations is the adjusted liquid-to-gas ratio discussed in the previous subsection.

Packed-Tower Absorber Diameter

The main parameter that affects the diameter of a packed column is the gas velocity at which liquid droplets become entrained in the exiting gas stream. Consider a packed column operating at set gas and liquid flow rates. If the gas velocity through the column is gradually increased by using smaller and smaller diameter columns, a point is reached where the liquid flowing down over the packing begins to be held in the void spaces between the packing. This gas velocity is termed the loading point. The pressure drop across the column also increases as the velocity increases and the degree of mixing between the phases decreases. A further increase in gas velocity beyond the loading point causes the liquid to completely fill the void spaces in the packing. The liquid forms a layer over the top of the packing, and no more liquid can flow down through the tower. This condition is referred to as *flooding*, and the gas velocity at which it occurs is the *flooding velocity*. Using an extremely large diameter tower would eliminate this problem; however, as the diameter increases, the cost of the tower increases, and a point will be reached where the liquid flow rate is insufficient to wet all of the packing.

Normal practice is to fix the diameter of the packed column so that the gas velocity is at a certain percent of the flooding velocity, typically 50% to 75%. It is assumed that by operating in this range, the gas velocity will also be below the loading point.

A common and relatively simple procedure for estimating the flooding velocity (thus setting a minimum column diameter) is to use a generalized flooding and pressure drop correlation such as the Sherwood correlation shown in Figure 5-23. The correlation is based on the physical properties of the gas and liquid streams and on the tower packing characteristics. The use of the Sherwood correlation is described below.

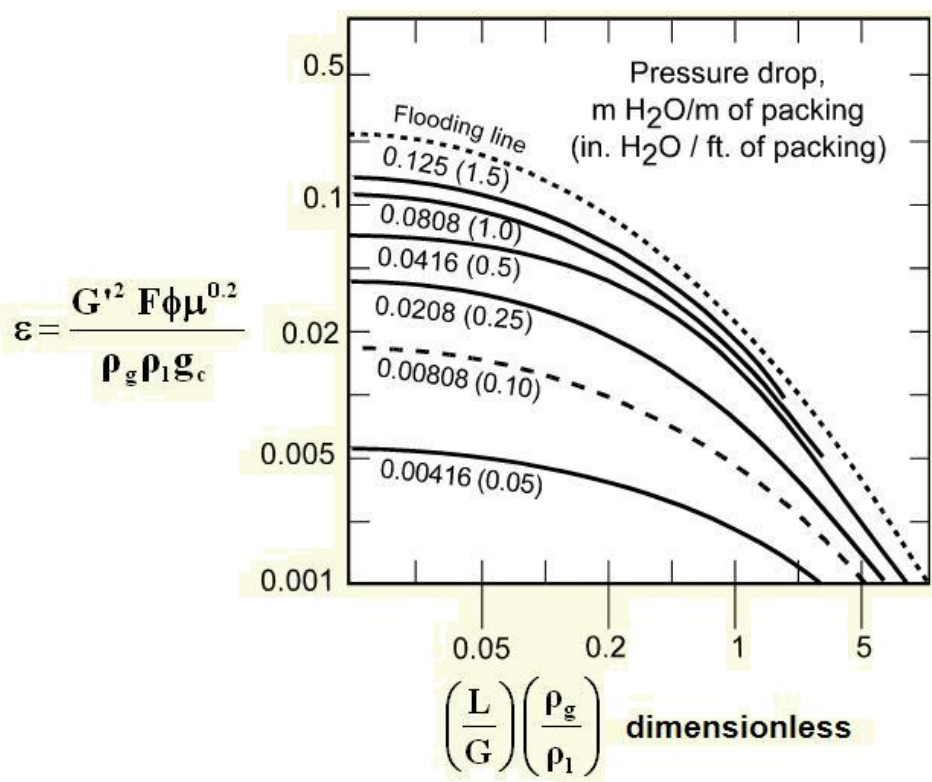


Figure 5-23. Generalized Sherwood flooding and pressure drop correlation.

Step 1. Calculate the value of the abscissa (horizontal axis) of Figure 5-23 using Equation 5-12.

(Eq. 5-12)
$$\text{Abscissa} = \left(\frac{L}{G} \right) \left(\frac{\rho_g}{\rho_l} \right)^{0.5}$$

Where:

- L = mass velocity of liquid stream, lb/ft² sec
- G = mass velocity of gas stream, lb/ft² sec
- ρ_g = gas density, lb/ft³
- ρ_l = liquid density, lb/ft³

Calculation of the individual values of L and G requires that the cross-sectional area of the column (and thus the column diameter) be known. However, the ratio (L/G) is simply the ratio of the mass flow rates and is independent of column diameter.

Step 2. From this point on the abscissa, move vertically up to the flooding line and read the ordinate, ϵ , at the flooding point.

Step 3. Calculate the gas mass velocity at flooding using Equation 5-13.

$$\text{(Eq. 5-13)} \quad G^* = \left(\frac{\epsilon \rho_g \rho_l g_c}{F_p \phi \mu^{0.2}} \right)^{0.5}$$

Where:

- G^* = gas mass velocity at flooding ($\text{lb}_m/\text{ft}^2 \cdot \text{sec}$)
- ϵ = ordinate of Sherwood correlation (Figure 5-23)
- ρ_g = density of gas (lb_m/ft^3)
- ρ_l = density of liquid (lb_m/ft^3)
- g_c = gravitational acceleration ($32.2 \text{ lb}_m \cdot \text{ft}/\text{lb}_f \cdot \text{sec}^2$)
- F_p = packing factor, ft^2/ft^3
- ϕ = specific gravity of absorbent (dimensionless)
- μ_l = viscosity of liquid (cP)

It is important to recognize that the ordinate of Figure 5-23 is not dimensionless, and the stated units must be used. Values of the packing factor, F_p , along with other properties of typical packing materials may be found in Table 5-2.

Step 4. Calculate the actual gas mass flow rate per unit area as a fraction of the gas flow rate at flooding (Equation 5-14).

$$\text{(Eq. 5-14)} \quad G_{op} = G^* f$$

Where:

- G_{op} = actual gas mass flow rate per unit area ($\text{lb}_m/\text{ft}^2 \cdot \text{sec}$)
- f = fractional approach to flooding, typically ≈ 0.75

Step 5. Calculate the packed bed diameter based on the actual gas mass velocity.

$$\text{(Eq. 5-15)} \quad \text{Tower Area, ft}^2 = \frac{\text{Total gas mass flow rate, lb}_m/\text{sec}}{\text{Gas mass velocity, lb}_m/\text{ft}^2 \cdot \text{sec}}$$

$$\text{(Eq. 5-16)} \quad \text{Tower Diameter} = \left[\frac{4 \times \text{Tower Area}}{\pi} \right]^{0.5}$$

$$\text{(Eq. 5-17)} \quad \text{Tower Diameter} = 1.13 (\text{Tower Area})^{0.5}$$

Table 5-2. Packing data.*					
Packing	Size (in.)	Weight (lb _m /ft ³)	Surface Area (ft ² /ft ³)	Void Fraction (%)	Packing Factor, F _p (ft ² /ft ³)
Raschig™ Rings (Ceramic, Porcelain)	1.0	44	58	70	155
	1.5	42	36	72	95
	2.0	38	28	75	65
	3.0	34	19	77	37
Raschig™ Rings (Steel)	1.0x1/32	40	63	92	115
	2.0x1/16	38	31	92	57
Berl™ Saddles (Ceramic Porcelain)	1.0	48	79	68	110
	2.0	38	32	75	45
Intalox™ Saddles (Ceramic)	1.0	44	78	77	98
	2.0	42	36	79	40
Intalox™ Saddles (Plastic)	1.0	6.0	63	91	30
	2.0	3.8	33	93	20
	3.0	3.3	27	94	15
Pall™ Rings (Plastic)	1.0	5.5	63	90	52
	2.0	4.5	31	92	25
Pall™ Rings (Metal)	1.5 x 0.03	24	39	95	28
Tellerettes™	1.0	7.5	55	87	40
	2.0	3.9	38	93	20
	3.0	5.0	30	92	15

* Data for guide purposes only. Packing factor for the specific application should be obtained from the manufacturer or from other sources.

Problem 5-3 illustrates the calculation procedures for estimating the packed bed column diameter.

Problem 5-3

For the scrubber in Problem 5-2, determine the packed-bed tower diameter if the operating liquid flow rate is 1.5 times the minimum. The gas velocity should be no greater than 75% of the flooding velocity, and the packing material is two-inch ceramic Intalox™ saddles.

Solution:

Step 1. Calculate the value of the abscissa in Figure 5-23.

From Problem 5-2:

$$G_m = 3540 \text{ g mole/min}$$

$$L = 3670 \text{ g mole/min}$$

Convert gas molar flow to a mass flow, assuming the gas to be air having a molecular weight of 29 g/g mole (air).

$$\begin{aligned} G &= (3540 \text{ g mole/min})(29 \text{ g/g mole}) \\ &= (102,700 \text{ g/min})(1 \text{ lb}_m/454 \text{ g}) = 226 \text{ lb}_m/\text{min} \end{aligned}$$

$$\begin{aligned} L &= (3670 \text{ g mole/min})(18 \text{ g/g mole}) \\ &= (66060 \text{ g/min})(1 \text{ lb}_m/454 \text{ g}) = 146 \text{ lb}_m/\text{min} \end{aligned}$$

The densities of air and water at 293 K are:

$$\rho_l = 62.4 \text{ lb}_m/\text{ft}^3$$

$$\rho_g = 0.074 \text{ lb}_m/\text{ft}^3 \text{ (from ideal gas law)}$$

Calculate the abscissa using Equation 5-11.

$$\text{Abscissa} = \left(\frac{L}{G} \right) \left(\frac{\rho_g}{\rho_l} \right)^{0.5} = \left(\frac{146}{226} \right) \left(\frac{0.074}{62.4} \right)^{0.5} = 0.0222$$

Step 2. Determine the ordinate in Figure 5-25 at an abscissa of 0.0222; the ordinate is 0.1.

Step 3. Calculate the gas flow rate per unit area at flooding.

$$G^* = \left(\frac{\epsilon \rho_g \rho_l g_c}{F_p \phi \mu_1^{0.2}} \right)^{0.5}$$

For water at 293K, $\phi = 1.0$, and the viscosity is equal to 1 cP.

From Table 5-2, for two-inch ceramic Intalox™ saddles:

$$F_p = 40 \text{ ft}^2/\text{ft}^3$$

$$g_c = 32.2 \text{ ft lb}_m/\text{lb}_f \text{ sec}^2$$

$$G^* = \left(\frac{(0.10)(0.074)(62.4)(32.2)}{40(1.0)(1^{0.2})} \right)^{0.5}$$

$$G^* = 0.61 \text{ lb}_m / \text{ft}^2 \text{ sec at flooding}$$

Step 4. Calculate the actual gas flow rate per unit area.

$$G_{op} = 0.75 (0.61) = 0.457 \text{ lb}_m / \text{ft}^2 \text{ sec}$$

Step 5. Calculate the tower diameter.

$$\text{Tower area} = \text{gas flow rate} / G_{op}$$

$$\frac{(226 \text{ lb}_m / \text{min})(1 \text{ min} / 60 \text{ sec})}{0.457 \text{ lb}_m / \text{ft}^2 \text{ sec}} = 8.24 \text{ ft}^2$$

$$\text{Tower diameter} = 1.13 A^{0.5} = 1.13(8.24)^{0.5} = 3.24 \text{ ft}$$

Pressure Drop:

Use Figure 5-25 once again. The new value of the ordinate based on the actual mass flow rate is:

$$(\epsilon_{new} / \epsilon_{old}) = (G_{act} / G_{flood})^2$$

$$\epsilon_{new} = 0.1(0.457 / 0.61)^2 = 0.056$$

Use the original abscissa value of 0.0222 and estimate:

$$\Delta P \approx 1 \text{ in W.C./ft packed height}$$

Packed-Tower Absorber Height

The height of a packed-tower absorber refers to the height of packing material needed to accomplish the required contaminant removal. The more difficult the separation, the larger the packing height required. For example, a much larger packed height would be required to remove SO_2 than to remove Cl_2 from an exhaust stream using water as the absorbent because Cl_2 is more soluble in water than SO_2 . Determining the proper height of packing is important because it affects both the rate and efficiency of absorption.

A number of theoretical equations based on diffusion principles are used to predict the required packing height. The general equation for a gas phase controlled resistance (common in air pollution systems) is given in Equation 5-18.

$$\text{(Eq. 5-18)} \quad Z = \frac{G}{K_g a} \int_{Y_2}^{Y_1} \frac{dY}{(1-Y)(Y-Y^*)}$$

Where: Z = height of packing (ft)
 K_g = overall gas film coefficient (lb moles/sec•ft²)

- G = molar flow rate of gas per unit cross sectional area
 (lb mol/ft²•sec)
 a = interfacial contact area per unit packing volume (ft²/ft³)
 Y = mole ratio of contaminant to contaminant-free gas
 Y^* = mole ratio of contaminant to contaminant-free gas at equilibrium

In Equation 5-18, the term $G/K_g a$ has the dimension of length and is referred to as the height of a transfer unit. The term inside the integral is dimensionless and represents the number of transfer units needed to make up the total packing height. Using the concept of transfer units, Equation 5-18 can be simplified to Equation 5-19.

(Eq. 5-19) $Z = (HTU)(NTU)$

Where: HTU = height of a transfer unit (ft)
 NTU = number of transfer units (dimensionless)

The concept of a transfer unit comes from the operation of tray-tower absorbers, where discrete stages (trays) of separation occur. These stages can be visualized as a transfer unit with the number and height of each giving the total tower height. Although packed columns operate as one continuous separation process, in design terminology the column is treated as if it were broken into discrete sections. The number and the height of a transfer unit may be based on either the gas or liquid phase so that Equation 5-19 can be modified to yield Equation 5-20.

(Eq. 5-20) $Z = N_{OG} H_{OG} = N_{OL} H_{OL}$

Where: N_{OG} = number of transfer units based on overall gas film coefficient
 H_{OG} = height of a transfer unit based on overall gas film coefficient (ft)
 N_{OL} = number of transfer units based on overall liquid film coefficient
 H_{OL} = height of a transfer unit based on overall liquid film coefficient (ft)

Values for the height of a transfer unit are usually obtained from experimental data. To ensure the greatest accuracy, vendors of absorption equipment normally perform pilot plant studies to determine the height of a transfer unit. For common absorption systems, such as NH_3 in water, manufacturers have developed correlations that can be used to estimate the height of a transfer unit. These correlations do not provide the accuracy of pilot plant data, but they are less expensive, less time consuming, and are easier to use.

Figure 5-23 gives a typical correlation for the ammonia-water system for two common packing materials. In this figure, the liquid mass velocity (lb_m/hr ft²) is

plotted versus the H_{OG} at a gas mass velocity of $500 \text{ lb}_m/\text{hr ft}^2$ with the two lines representing different packing materials. In applying these data, it is important that the process conditions be similar to the conditions at which the HTU was measured.

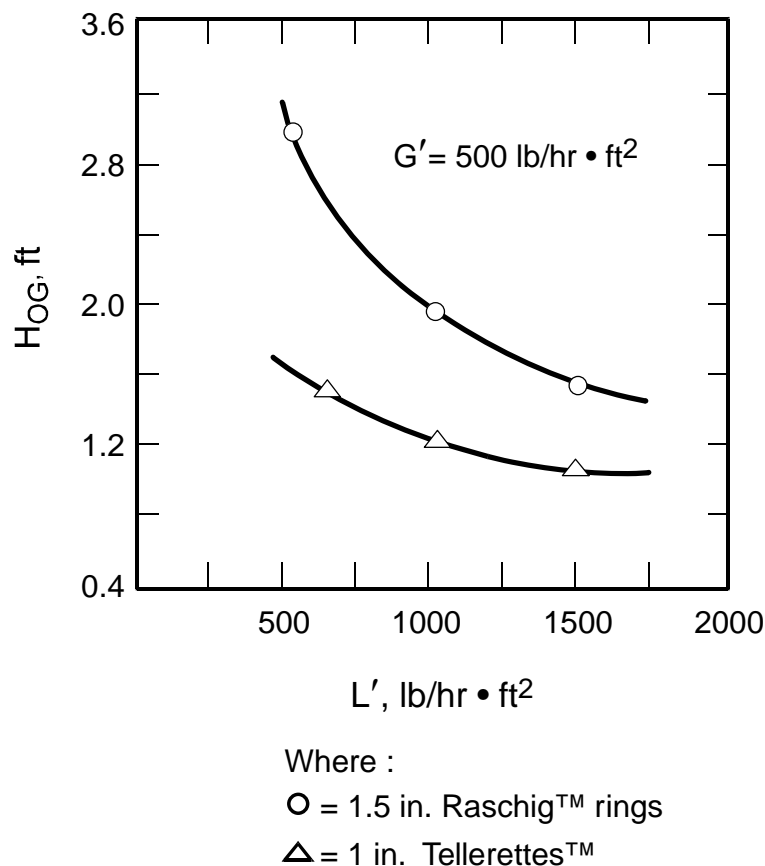


Figure 5-24. Height of a transfer unit, ammonia and water system.

When no experimental data are available, or if only a preliminary estimate of absorber efficiency is needed, generalized correlations are available to estimate the height of a transfer unit. The correlations for predicting the H_{OG} or the H_{OL} are empirical and are functions of the type of packing, liquid and gas flow rates, concentration and solubility of the contaminant, liquid properties, and system temperature. These correlations can be found in engineering texts. For most applications, the height of a transfer unit ranges between 1 and 4 feet (0.305 and 1.22 m).

The number of transfer units, NTU, can be obtained experimentally or calculated by a variety of methods. When the pollutant concentration is low, and the equilibrium line is straight, Equation 5-21 can be used to determine the number of transfer units (N_{OG}) based on the gas phase resistance. Equation 5-21 can be derived from the integral portion of Equation 5-18 when the above restrictions are satisfied.

$$\text{(Eq. 5-21)} \quad N_{\text{OG}} = \frac{\ln \left[\frac{(Y_1 - m X_2)}{(Y_2 - m X_2)} \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right) \right]}{1 - \frac{m G_m}{L_m}}$$

Where: Y_1 = mole ratio of contaminant to contaminant-free gas entering the absorber
 m = slope of the equilibrium line (= Henry's Law constant)
 X_2 = mole ratio of contaminant to contaminant-free liquid entering the absorber
 Y_2 = mole ratio of contaminant to contaminant-free gas leaving the absorber
 G_m = molar flow rate of gas (lb mole/hr)
 L_m = molar flow rate of liquid (lb mole/hr)

Equation 5-21 may be solved arithmetically or graphically by using the Colburn diagram presented in Figure 5-25. The Colburn Diagram is a plot of the N_{OG} versus $\ln[(Y_1 - mX_2)/(Y_2 - mX_2)]$ at various values of (mG_m/L_m) . Figure 5-25 is used by first computing the value of $\ln[(Y_1 - mX_2)/(Y_2 - mX_2)]$, reading up the graph to the line corresponding to the appropriate value of (mG_m/L_m) , and then reading across to obtain the N_{OG} .

Equation 5-21 can be further simplified for special situations where a chemical reaction occurs or if the pollutant is extremely soluble. In these cases, the pollutant exhibits almost no partial pressure, and, therefore, the slope of the equilibrium line approaches zero ($m = 0$). For these cases, Equation 5-21 reduces to Equation 5-22.

$$\text{(Eq. 5-22)} \quad N_{\text{OG}} = \ln \left(\frac{Y_1}{Y_2} \right)$$

The number of transfer units depends only on the inlet and outlet concentration of the pollutant. For example, if the conditions in Equation 5-22 are met, 2.3 transfer units are required to achieve 90% removal of any pollutant.

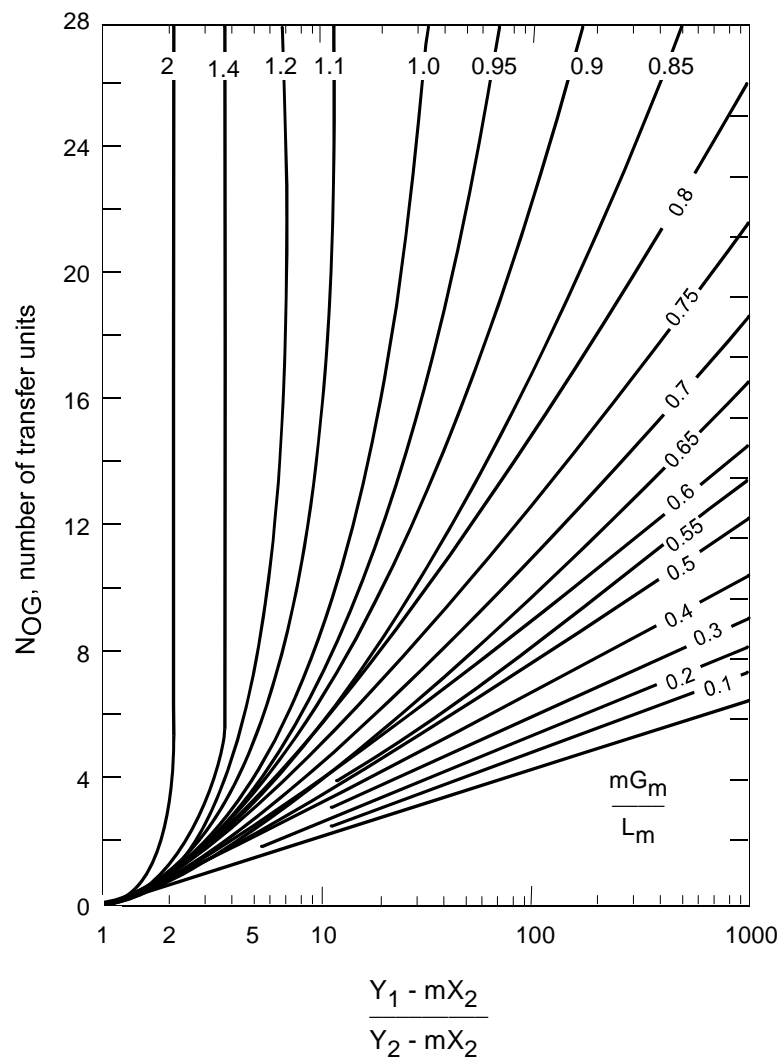


Figure 5-25. Colburn diagram.

Problem 5-4

Continue Problems 5-1 through 5-3 by estimating the required packed height. In order to calculate HOG, use the correlation for 1.5-inch Raschig rings in Figure 5-24 as a substitute for the 2-inch Intalox saddles specified in the earlier examples.

Solution:

Use data from previous problems.

$$m = 0.772 \text{ mole ratio NH}_3 \text{ in air / mole ratio NH}_3 \text{ in water}$$

$$G = 226 \text{ lb}_m/\text{min}$$

$$L = 146 \text{ lb}_m/\text{min}$$

$$X_2 = 0 \text{ (no recirculated liquid)}$$

$$Y_1 = 0.03$$

$$Y_2 = 0.003$$

Step 1. Convert mass to molar flow rates.

$$G_m = (226 \text{ lb}_m/\text{min})(\text{lb mole}/29 \text{ lb}_m) = 7.79 \text{ lb mole}/\text{min}$$

$$L_m = (146 \text{ lb}_m/\text{min})(\text{lb mole}/18 \text{ lb}_m) = 8.11 \text{ lb mole}/\text{min}$$

Step 2. Compute the N_{OG} from Equation 5-21.

$$N_{OG} = \frac{\ln \left[\frac{(Y_1 - m X_2) \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right)}{(Y_2 - m X_2) \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right)} \right]}{1 - \frac{m G_m}{L_m}}$$

$$N_{OG} = \frac{\ln \left[\frac{(0.03) \left(1 - \frac{(0.772)(7.79)}{8.11} \right) + \left(\frac{(0.772)(7.79)}{8.11} \right)}{(0.003) \left(1 - \frac{(0.772)(7.79)}{8.11} \right) + \left(\frac{(0.772)(7.79)}{8.11} \right)} \right]}{1 - \frac{(0.772)(7.79)}{8.11}}$$

$$N_{OG} = 4.65$$

Step 3. Obtain H_{OG} from Figure 5-24.

$$L' = (146 \text{ lb}_m/\text{min})(60 \text{ min}/\text{hr})(1/5.84 \text{ ft}^2) = 1500 \text{ lb}_m/\text{hr ft}^2$$

$$H_{OG} = 1.6 \text{ ft}$$

Step 4. The total packing height is:

$$Z = (H_{OG})(N_{OG}) = (1.6 \text{ ft})(4.65) = 7.44 \text{ ft}$$

Total Pressure Drop:

$$\Delta P_{\text{tot}} = (1 \text{ in. W.C.}/\text{ft})(7.44 \text{ ft}) \approx 7.44 \text{ in W.C.}$$

Tray-Tower Absorber Diameter and Height

In a tray-tower absorber, the liquid enters at the top of the tower, passes over the top tray, and then down over each lower tray until it reaches the bottom as shown in Figure 5-26. Absorption occurs as the gas, which enters at the bottom, passes up through the tray and contacts the liquid. In a tray tower, absorption occurs in a stepwise manner or in a stage process. Liquid and gas concentrations at the top of the tower are designated X_a and Y_a , respectively. Bottom concentrations are designated X_b and Y_b . Trays are numbered consecutively from 1 at the top to n at the bottom of the tower. Gas and liquid concentrations within the tower are subscripted according to the tray from which each originates.

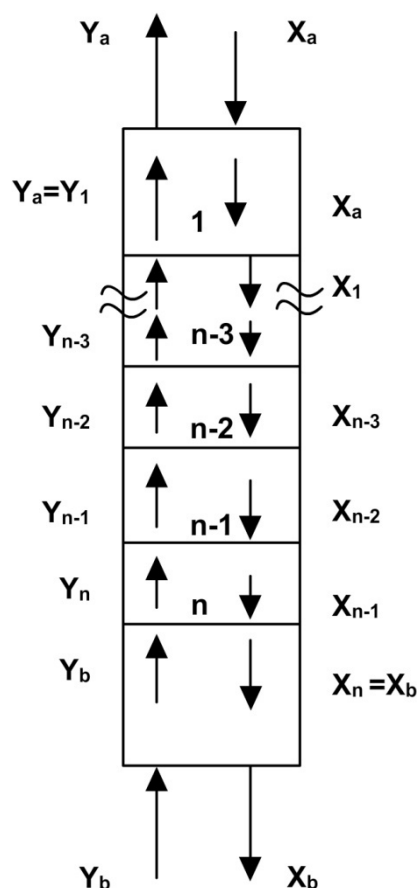


Figure 5-26. Schematic diagram of a tray-tower absorber.

There are various accepted procedures available for sizing a tray tower. Detailed summaries can be found in standard chemical engineering references.^{8,9,10} The following discussion presents a simplified method for sizing or reviewing the design of a tray tower.

Tray Tower Diameter

The minimum diameter of a single-pass tray tower is determined based on the gas velocity through the tower. If the gas velocity is too great, liquid droplets are entrained to the tray above. This condition, known as priming, reduces absorber efficiency. Priming in a tray tower is somewhat analogous to flooding in a packed tower in that it determines the minimum acceptable diameter. The actual tower diameter should be larger. Equation 5-23 expresses the smallest allowable diameter for a tray-tower absorber.

$$\text{(Eq. 5-23)} \quad d = \Psi \left(Q \sqrt{\rho_g} \right)^{0.5}$$

Where: Ψ = empirical constant ($\text{ft}^{0.25} \cdot \text{min}^{0.5} / \text{lb}^{0.25}$)
 Q = volumetric gas flow rate (ft^3 / min)

$$\rho_g = \text{gas density (lb}_m/\text{ft}^3)$$

The term Ψ is a function of the tray spacing and the densities of the gas and liquid streams. Values for Ψ in Table 5-3 are for a tray spacing of 61 cm (24 in) and a liquid specific gravity of 1.05.¹¹ If the specific gravity of a liquid varies significantly from 1.05, the values for Ψ in Table 5-3 cannot be used.

Table 5-3. Tray spacing parameters.¹¹		
Tray	Metric*	English**
Bubble Cap	0.0162	0.1386
Sieve	0.0140	0.1198
Valve	0.0125	0.1069

* Metric expressed in $\text{m}^{0.25} \cdot \text{hr}^{0.5} / \text{kg}^{0.25}$ for use with Q expressed in m^3/hr , and ρ_g expressed in kg/m^3 .

** English expressed in $\text{ft}^{0.25} \cdot \text{min}^{0.5} / \text{lb}^{0.25}$ for use with Q in ACFM, and ρ_g expressed in lb/ft^3 .

Trays are spaced sufficiently far apart to allow the gas and liquid phases to separate before reaching the plate above and also to provide space for easy maintenance and cleaning. They are normally spaced 45 cm to 70 cm (18 to 28 in.) apart. The use of Table 5-3 for tray spacing different than 61 cm (24 in.) requires that the diameter calculated from Equation 5-23 be multiplied by a correction factor that is obtained from Figure 5-27.

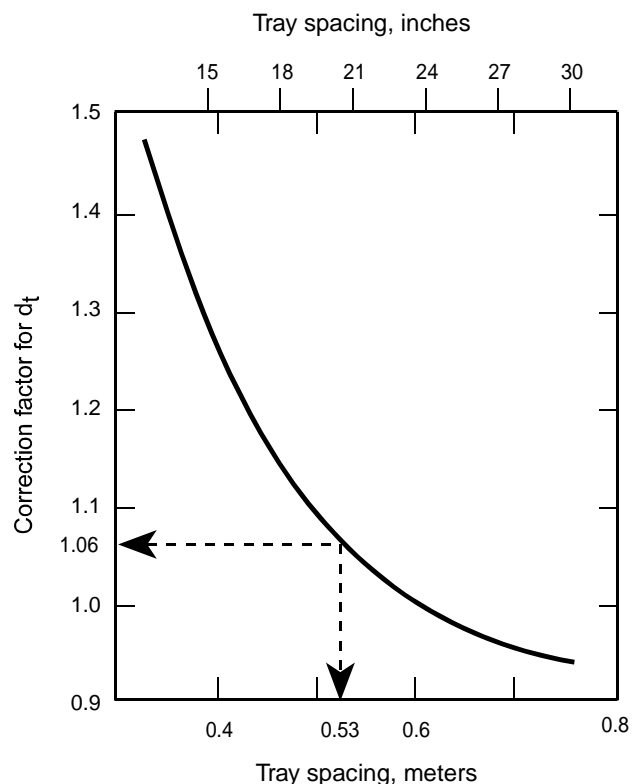


Figure 5-27. Tray spacing correction factor.

Problem 5-5 illustrates how the minimum diameter of a tray-tower absorber is estimated.

Problem 5-5

For the conditions described in Problem 5-2, determine the minimum acceptable diameter if the scrubber is a bubble-cap tray-tower absorber. The trays are spaced 0.53 m (21 in.) apart. Use a liquid density of 1030 kg/m³.

Solution:

From Problem 5-2:

$$\text{Gas flow rate} = Q = 85.0 \text{ m}^3/\text{min}$$

$$\text{Density} = \rho_g = \left(\frac{\text{g mole}}{0.024 \text{ m}^3} \right) \left(\frac{29 \text{ gm}}{\text{g mole}} \right) \left(\frac{\text{kg}}{1000 \text{ gm}} \right) = 1.21 \text{ kg/m}^3$$

From Table 5-2 for a bubble-cap tray:

$$\Psi = 0.0162 \text{ m}^{0.25} \cdot \text{hr}^{0.50} / \text{kg}^{0.25}$$

Before Equation 5-22 can be used, Q must be converted to m³/hr.

$$Q = (85.0 \text{ m}^3/\text{min})(60 \text{ min/hr}) = 5100 \text{ m}^3/\text{hr}$$

Step 1. Substitute these values into Equation 5-22 to obtain the minimum diameter.

$$d = \psi(Q\sqrt{\rho_g})^{0.5}$$

$$d = (0.0162)[5100 (1.21)^{0.5}]^{0.5} = 1.21 \text{ m}$$

Step 2. Correct the diameter for a tray spacing of 0.53 m.

From Figure 5-27, read a correction factor of 1.06.

Therefore, the minimum diameter is:

$$d = 1.21 (1.06) = 1.28 \text{ m (4.20 ft)}$$

Note: This is the minimum acceptable diameter based on the operating conditions. In practice, a larger diameter should be specified.

Number of Trays

There are several methods used to determine the number of ideal plates or trays required for a given removal efficiency. An ideal plate is defined as one in which the gas and liquid streams leaving the plate are in equilibrium with each other.

One method used is a graphical technique such as illustrated in Figure 5-28. The number of ideal plates is obtained by drawing “steps” on an operating diagram. The operating and equilibrium lines are determined as previously described. The liquid and gas concentrations at the bottom of the tower, X_b and Y_b , are known as is the gas concentration at the top of the tower, X_a . A horizontal line is drawn from A, which represents conditions at the bottom of the tower, to B on the equilibrium curve. Point B establishes the concentrations of the two streams leaving the bottom plate, X_n and Y_n , which, according to the definition of an ideal plate, are in equilibrium with each other. Next, a vertical line is drawn from B to C located on the operating line. Points on the operating line represent concentrations of streams that pass, in this case X_n and Y_{n-1} . This graphical stair-step procedure is repeated until concentrations at the top of the tower are reached. Each complete step represents one ideal tray.

In the Figure 5-28 example, conditions at the top of the tower lie between points E and F. Visual interpolation indicates that the point X_a , Y_a is about 0.3 of the distance between E and F. Thus, we estimate that 2.3 ideal trays are required for the specified separation. In effect, each horizontal line is a graphical statement that streams leaving an ideal tray are in equilibrium while each vertical line is a representation of a contaminant material balance at that position in the tower. In reality, equilibrium on each tray may be approached, but never truly achieved. To account for this, the number of actual trays will be greater than the ideal trays based on an efficiency correction that is described below.

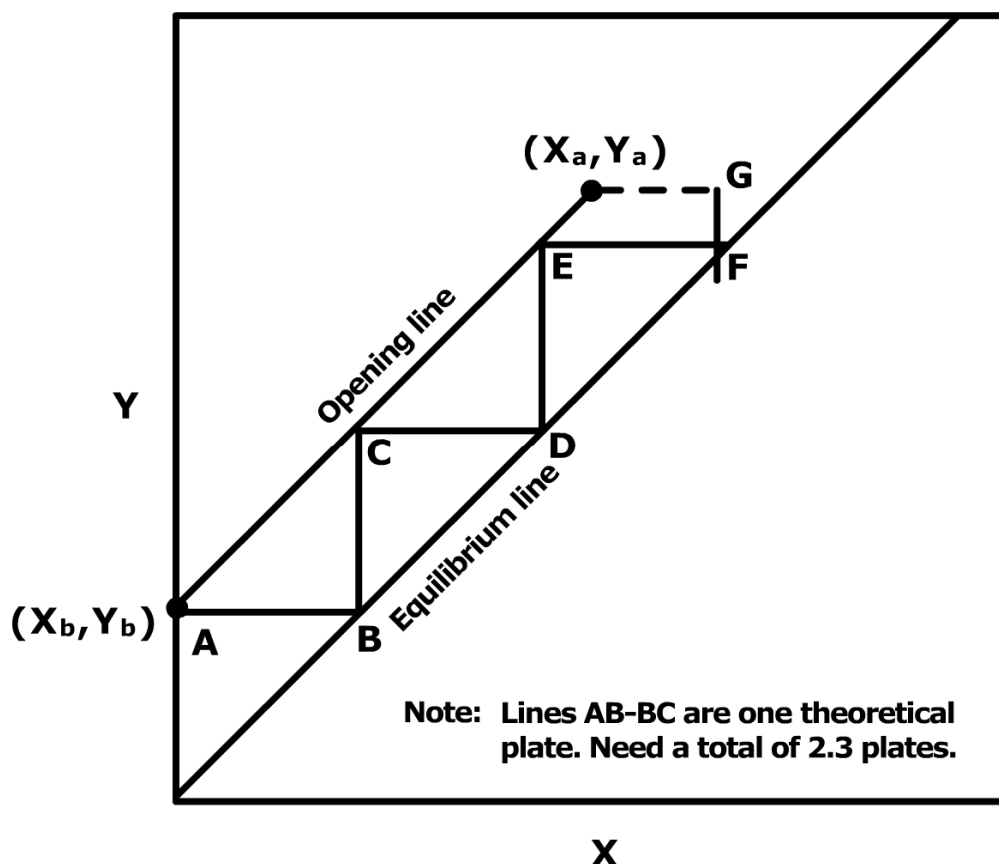


Figure 5-28. Graphical determination of the number of theoretical plates.

When both the equilibrium and operating lines are straight, which is often the case in air pollution problems, the number of ideal trays can be calculated analytically using Equation 5-24. Note that Equation 5-24 is similar but not identical to Equation 5-21 for computing the N_{OG} of a packed tower.

$$(Eq. 5-24) \quad N_{OG} = \frac{\ln \left[\frac{(Y_1 - m X_2) \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right)}{(Y_2 - m X_2) \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right)} \right]}{\ln \left(\frac{L_m}{m G_m} \right)}$$

Equation 5-24 is used to predict the number of theoretical trays required to achieve a given removal efficiency. The operating conditions for a theoretical tray assume that the gas and liquid streams leaving the plate are in equilibrium with each other. This ideal condition is never achieved in practice. A larger number of actual trays are required to compensate for this decreased tray efficiency.

Three types of efficiencies have been proposed to correct for the fact that true equilibrium is not actually achieved: (1) the overall efficiency, which is applied equally to all trays within the column; (2) the Murphree efficiency, which

may vary from tray to tray; and (3) the local efficiency, which pertains to a specific location on a tray. While methods for estimating the Murphree and local efficiencies are available, the methods are complex and are of questionable reliability.

For the present purposes, the overall efficiency, which is the ratio of the number of theoretical trays to the actual number of trays, is satisfactory. Values of the overall efficiency are often based on operating experience with systems that are similar to the system of current interest. For a rough estimate, overall tray efficiencies for absorbers operating with low-viscosity liquid normally fall in the 20% to 40% range for gas streams having high inert gas concentrations (typical air pollution control applications).

Problem 5-6

Calculate the number of theoretical trays required for the NH_3 absorber considered in the previous example problems. Estimate the total height of the absorber if the trays are spaced at 0.53 m intervals, and assume an overall tray efficiency of 40%.

Solution:

From Problem 5-5 and the previous examples, the following data is obtained.

$$\begin{aligned} Y_1 &= 0.03 \\ Y_2 &= 0.003 \\ X_2 &= 0 \\ L_m &= 3680 \text{ g mole H}_2\text{O/min} \\ G_m &= 3540 \text{ g mole air/min} \\ m = H_y &= 0.772 \end{aligned}$$

Step 1. The number of theoretical plates from Equation 5-24 is:

$$N_{\text{OG}} = \frac{\ln \left[\frac{(Y_1 - m X_2) \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right)}{(Y_2 - m X_2) \left(1 - \frac{m G_m}{L_m} \right) + \left(\frac{m G_m}{L_m} \right)} \right]}{\ln \left(\frac{L_m}{m G_m} \right)}$$

$$N_{\text{OG}} = \frac{\ln \left[\frac{(0.03 - 0) \left(1 - \frac{(0.772)(3540)}{3630} \right) + \left(\frac{(0.772)(3540)}{3630} \right)}{(0.003 - 0) \left(1 - \frac{(0.772)(3540)}{3630} \right) + \left(\frac{(0.772)(3540)}{3630} \right)} \right]}{\ln \left(\frac{3630}{(0.772)(3540)} \right)}$$

$$N_{\text{OG}} = 4.1 \text{ theoretical plates}$$

Step 2. Assuming that the overall plate efficiency is 40%, the actual number of trays is:

$$\text{Actual plates} = 4.1/0.40 \approx 10.3 \text{ trays}$$

Step 3. The height of the tower is given by:

$$Z = N_p \times \text{tray spacing} + \text{top height}$$

The top height is the distance over the top plate that allows the gas-vapor mixture to separate. This distance (sometimes termed the *freeboard*) is usually the same as the tray spacing.

$$Z = 10.3 \text{ trays (0.53 m/tray)} + 0.53 \text{ m}$$

$$Z = 6.0 \text{ meters (17.2 ft)}$$

This height of the tray-tower absorber calculated in Problem 5-6 is higher than the 7.4 ft estimated for the packed tower in Problem 5-4. This is logical because the tray tower is often less efficient for gas absorption than a similarly sized packed-bed scrubber. Because of the many assumptions and simplifications made in these example problems, no generalization should be made concerning the relative capabilities of the two common types of absorbers.

Mist Eliminator Evaluation

There are limits to the gas velocity through the mist eliminator since, at high gas velocities, liquid can be forced toward the trailing edge of the mist eliminator elements and reentrained in the gas stream. General guidelines concerning the maximum velocities are presented in Table 5-4.

Table 5-4. Gas velocities through mist eliminators. ¹²		
Mist Eliminator Type	Orientation	Maximum Gas Velocity (ft/sec)
Zigzag*	Horizontal	15 - 20
Zigzag*	Vertical	12 - 15
Mesh Pad	Horizontal	15 - 23
Mesh Pad	Vertical	10 - 15
Woven Pad ¹³	Vertical	7 - 15
Tube Bank	Horizontal	18 - 23
Tube Bank	Vertical	12 - 16

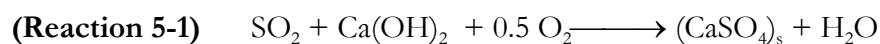
*Termed *chevron* in remainder of manual

The actual maximum velocity that applies to the specific type of mist eliminator should be determined from the manufacturers' specification sheet. This data can then be used to confirm that the mist eliminator is located in an area where the gas velocity is below the maximum level. The average gas velocity through the mist eliminator can be calculated simply by dividing the actual gas flow rate by the open area of the mist eliminator, as shown in Equation 5-25.

$$\text{(Eq. 5-25)} \quad \text{Velocity} = \frac{\text{Gas flow rate, ft}^3/\text{min}}{\text{Mist eliminator open area, ft}^2} \left(\frac{\text{min}}{60 \text{ sec}} \right)$$

Alkali Requirements

Absorption systems may require an alkali addition system if the gas stream is acidic. The most common acid gases are sulfur dioxide, hydrogen chloride, and hydrogen fluoride. Carbon dioxide, which is formed in all combustion processes involving fossil fuels, wood fuels, and waste fuels, is also acidic. Calcium hydroxide $[\text{Ca}(\text{OH})_2]$ is the most common alkali material used to neutralize the acid gas. The alkali requirement is usually calculated based on the quantity of acid gas and the stoichiometry of the neutralization reaction.



Problem 5-7

Calculate the amount of calcium hydroxide (lime) needed to neutralize the HCl absorbed from a gas stream having 50 ppm HCl and a flow rate of 10,000 SCFM. Assume an HCl neutralization efficiency of 95%.

Solution:

The quantity of HCl absorbed in the scrubbing liquid is calculated as follows:

$$\text{HCl} = 10,000 \text{ SCFM} \left(\frac{\text{lb mole}}{385.4 \text{ SCF}} \right) \left(\frac{0.00005 \text{ lb mole HCl}}{\text{lb mole total}} \right) \left(\frac{95\% \text{ efficiency}}{100\%} \right)$$

$$\text{HCl} = 0.00123 \text{ lb mole HCl/min}$$

$$\text{Ca}(\text{OH})_2 \text{ required} = \left(\frac{1 \text{ lb mole Ca}(\text{OH})_2}{2 \text{ lb mole HCl}} \right) \left(\frac{0.00123 \text{ lb mole HCl}}{\text{min}} \right)$$

$$= \frac{0.000615 \text{ lb mole Ca}(\text{OH})_2}{\text{min}}$$

$$\begin{aligned} \text{Ca}(\text{OH})_2 \text{ req} &= 0.00062 \text{ lb mole/min} \quad (74 \text{ lb/lb mole}) = 0.0455 \text{ lb/min} \\ &= 2.73 \text{ lb/hour} \end{aligned}$$

The alkali feed system should be designed to provide sufficient alkali during times of peak acid gas concentrations. In some processes, the acid gas concentration can vary by more than a factor of 2. If these peaks last for long periods of time, the alkali system must have sufficient capacity to prevent the

pH from dropping to values less than approximately 5, where the rate of corrosion begins to accelerate, especially in the presence of chlorides and fluorides.

5.4 Instrumentation

Standard Absorbers

Properly designed and operated absorption systems usually work very well; however, a variety of operating problems can occur in essentially any absorber. The most common problems affecting absorbers used for air pollution control include the following:

- Inadequate recirculation liquid flow
- Poor gas-liquid contact
- Inadequate alkali feed rates to neutralize acids
- Excessive liquid temperatures
- Corrosion

The system shown in Figure 5-29 is a three-tray impingement tray absorber with a mesh pad mist eliminator. A recirculation tank and alkali feed equipment are included in the system. This system is used simply to illustrate the types of instruments that might be present on a large population of conventional absorption systems. These instruments might be required as part of a periodic monitoring program (e.g., Compliance Assurance Monitor [CAM]), or as part of an operating permit.

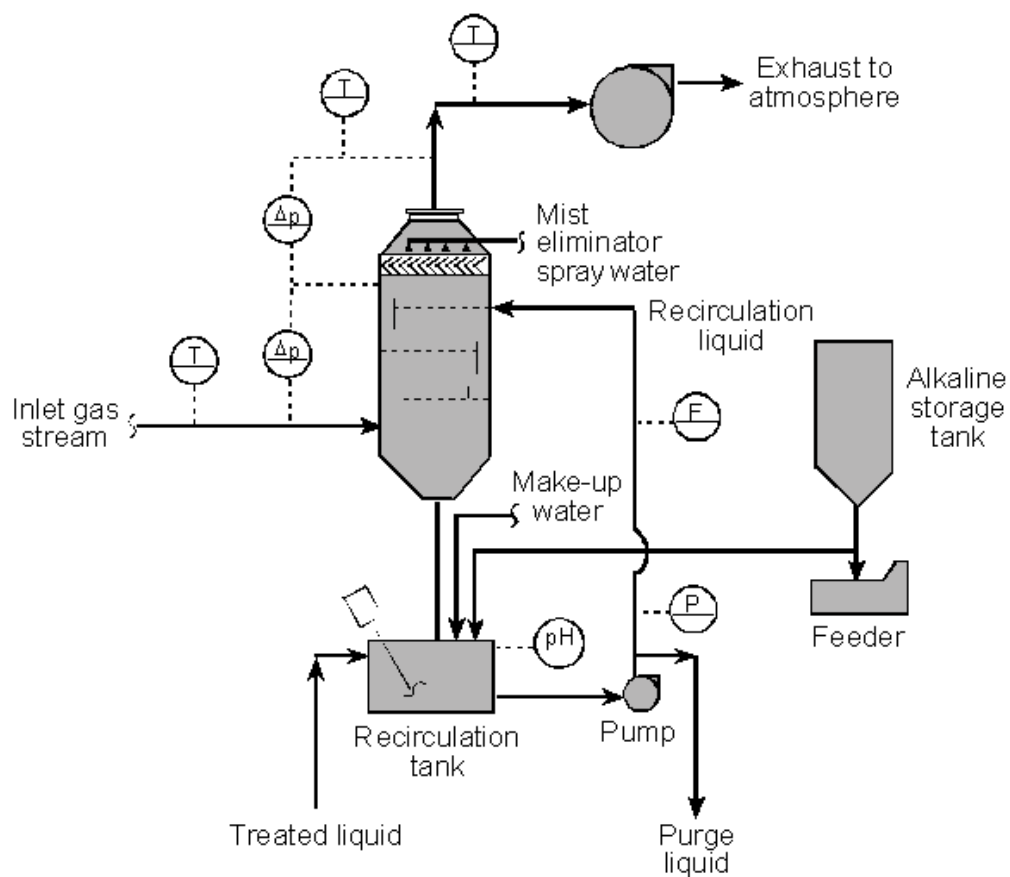


Figure 5-29. Performance monitoring instruments on an example absorber system.

The instrumentation provided in this example system measures inlet gas temperature, outlet gas temperature, recirculation liquid flow rate, liquid header pressure, pump discharge pressure, liquid pH, tray static pressure drop, and mist eliminator static pressure drop. This set of instruments is relatively typical for many absorber systems, but the liquid flow rate monitor is rarely included on small-scale systems.

No outlet concentration monitor has been included, because these instruments are difficult to use on saturated gas streams such as those found in absorbers. It is difficult to extract a gas sample and remove the condensed water without inadvertently removing some of the contaminant that has penetrated the scrubber. Furthermore, there are no commercially available concentration monitors for many of the gaseous contaminants of interest in absorption; therefore, less direct indicators of performance are used.

Mist Eliminator Static Pressure Drop

The static pressure drop across the mist eliminator provides an excellent indicator of the physical condition of the mist eliminator. The static pressure drop is strictly a function of the geometry of the mist eliminator, the gas flow rate through the mist eliminator, and the gas density. Accordingly, the static

pressure drop should be relatively constant. Increases from the baseline level are probably indicative of solids buildup. The pressure drops across mist eliminators usually vary from 0.5 to 2 in. W.C. (0.1 to 0.5 kPa), but some commercial designs have pressure drops as high as 4 in. W.C. (1.0 kPa). Solids accumulations can increase mist eliminator pressure drops by more than 1 in. W.C. (0.25 kPa).

If high pressure drop occurs, it may be necessary to activate the cleaning system more frequently or for a longer operating time. Mist eliminator washing usually lasts from several minutes to more than 15 minutes.

Mist eliminator static pressure drop well below the baseline range suggests that the mist eliminator has been damaged. Structural failure of the mist eliminator is possible because of the forces that can be imposed on the surface when it is significantly blinded. For example, a 6-foot-diameter mist eliminator immediately upstream of a fan with an inlet static pressure of -10 in. W.C. can create a force of over 1400 pounds-force on the surface. Corrosion-related weakening of the supporting frame of the mist eliminator could cause the entire unit to break into parts and be pulled toward the fan. Units constructed of FRP and other synthetic materials can suffer adhesive failure if there is a gas temperature spike, causing part of the mist eliminator to break away. The gaps left in the mist eliminator have a very low static pressure drop, and most of the gas stream channels through this area. Accordingly, the effectiveness of the unit is compromised.

Liquid Flow Rate

Liquid flow rate monitors on the recirculation line leading back to the absorber (Figure 5-29) provide an indirect indication of absorber performance. Large decreases in the liquid flow rate can result in inadequate gas-liquid contact. Large increases may result in the absorber approaching flooding conditions.

There are a variety of instruments used to monitor liquid flow rates, including:

1. magnetic flow meters
2. ultrasonic flow meters
3. orifice meters
4. swinging vane meters

The magnetic flow meters are usually used on moderate-to-large systems, and the other types are common on moderate-to-small systems. All of these units are vulnerable to high suspended-solids levels in the recirculation liquid. Solids can precipitate inside the pipe and blind the sensors of magnetic flow meters and ultrasonic meters. Suspended solids can erode orifice plates and block the movement of swinging vane meters.

Indirect indicators of liquid flow rate are useful in absorber systems that have vulnerable liquid flow meters because of the high suspended-solids levels. Indirect indications of decreases in the liquid flow rate include (1) a decrease in the recirculation pump discharge pressure and (2) an increase in the pressure in headers supplying spray nozzles at the top of the absorber vessel. Increased

pressure in the spray nozzle supply header is usually due to a plugged nozzle orifice or header itself.

Another indirect indicator of reduced liquid flow is the outlet gas temperature, which can increase from normal levels because of poor gas-liquid contact, caused in part by low liquid flow rates. The interpretation of outlet gas temperature data is discussed further in the following paragraph.

Outlet Gas Temperature

A temperature monitor in the outlet duct of the scrubber vessel is especially useful. The outlet gas stream temperature should be close to the adiabatic saturation temperature because of the relatively long contact time between the gas and liquid streams. The adiabatic saturation temperature is the temperature that is reached as heat is transferred from the gas to the liquid phase due to the vaporization of liquid. The term *adiabatic* means that heat transfer occurs only between the liquid and gas streams, and there is no net heat transfer into or out of the absorber. While this is not precisely the case, most large absorbers closely approximate adiabatic operation.

The adiabatic saturation temperature is estimated using a psychrometric chart, such as Figure 5-30. The inlet gas dry bulb temperature and dew point establish a point on the psychrometric chart representing inlet gas conditions. Adiabatic operation is represented by the dashed line running parallel to the wet bulb temperature lines. The dashed line intersects the saturation line at the adiabatic saturation temperature. The outlet absorber gas temperature should be close to this value when the absorber is operating properly.

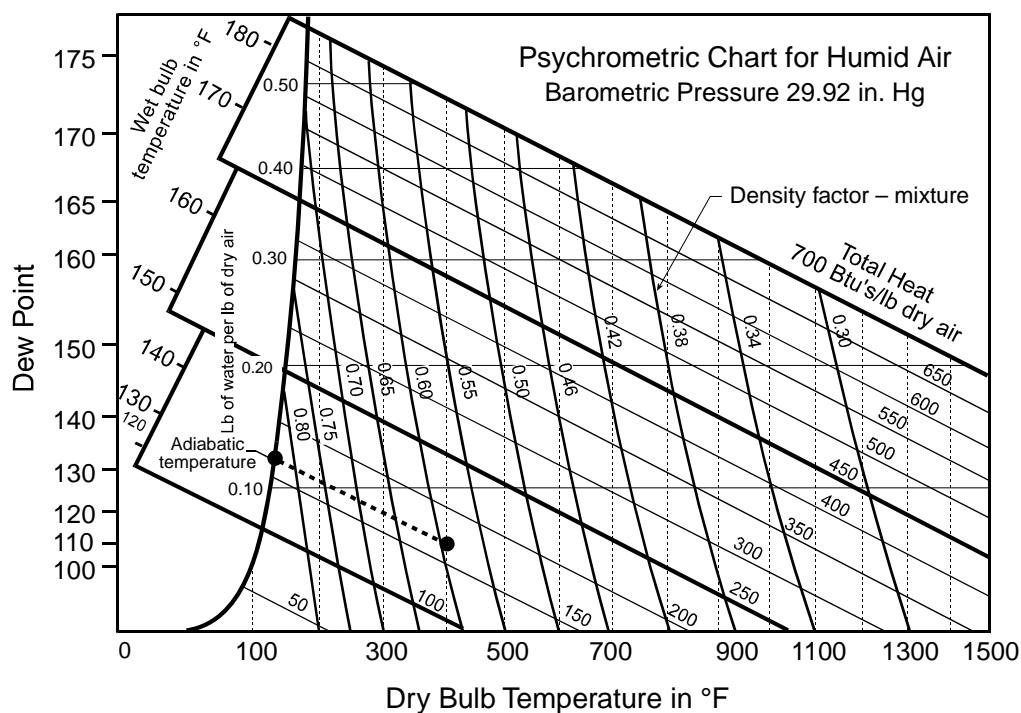


Figure 5-30. Psychrometric chart.

Absorber outlet gas temperatures more than 5°F to 10°F (2.7°C to 5.5°C) above the adiabatic saturation temperature are sometimes associated with significant gas-liquid maldistribution or inadequate recirculation liquid flow. Some of the conditions that could create gas-liquid maldistribution in the various types of absorbers are listed below.

Spray Towers

- Plugging of one or more spray nozzles
- Plugging of nozzle supply headers
- Maldistribution of the gas stream entering the vessel

Packed Bed

- Inadequate liquid distribution at the top and/or inadequate redistribution between beds
- Channeling due to plugging in the bed
- Collapse of one or more beds

Tray Towers

- Sloped, bowed, or warped trays
- Gas short-circuiting through incompletely filled liquid downcomers
- Sloped overflow weirs on one or more trays
- Solids accumulation in localized portions of the trays

Venturis

- Inadequate distribution of liquid across the inlet to the throat
- Gas maldistribution entering the converging area of the throat

Ejectors

- Inadequate distribution of liquid across the ejector section
- Erosion of the ejector nozzle

Column Static Pressure Drop

The absorber static pressure drop provides a useful indication of plugging in packed beds or impingement trays. Static pressure drops above baseline levels are usually caused by partial plugging.

A change in the gas flow rate through the system can be evaluated by checking the process operating rate and the fan motor currents. A decrease in the fan motor current is usually associated with a decrease in the gas flow rate through the absorber system.

Recirculation Liquid pH

Variations in the recirculation liquid pH levels are useful in evaluating absorber performance. The pH is usually monitored in the recirculation tank where alkali is added to the system or in the recirculation line leading back to the inlet of the absorber.

pH levels above 9 indicate the potential for the precipitation of calcium and magnesium compounds. These precipitates can cause plugging of spray nozzles, distributors, packed beds, and trays. Furthermore, the precipitates can accumulate as a layer inside the recirculation lines and restrict liquid flow. The decrease in liquid flow is not always apparent because of the adverse impact of the solids on the liquid flow rate monitors.

pH levels below approximately 5 indicate that insufficient alkali is being added to neutralize the acid gases being absorbed. Low removal efficiencies are probable because of the liquid stream's potential for saturation. When the pH is lower than 5, severe corrosion of metal components is possible. Corrosion is especially rapid when the low pH conditions occur in systems with high dissolved chloride or fluoride concentrations.

Biofiltration Systems

A schematic flowchart of a biofiltration system is shown in Figure 5-31. Permanent instrumentation on these systems may be limited, in which case portable instruments will be important in evaluating their performance.

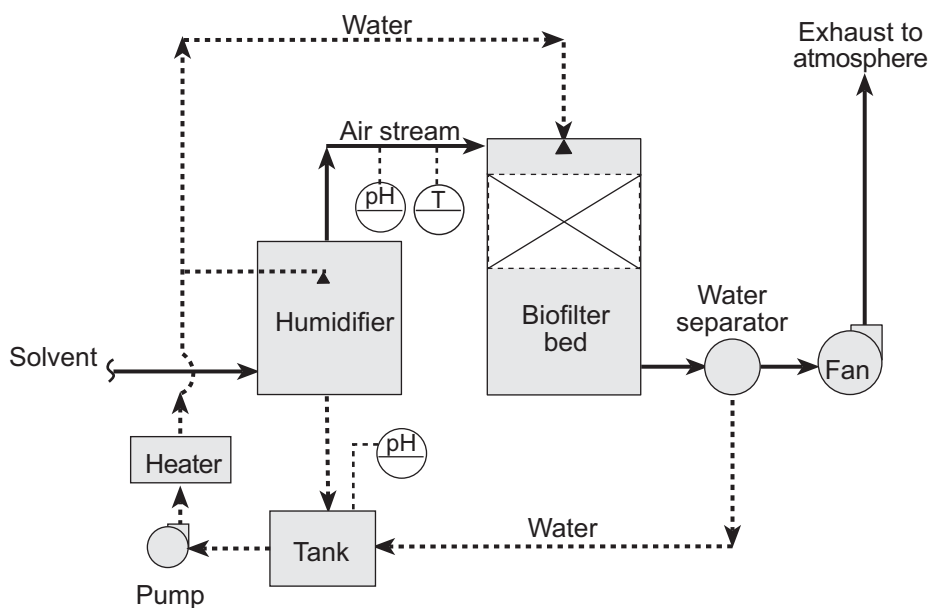


Figure 5-31. Flowchart of a typical biofiltration oxidation system.

Inlet Gas Temperature

Instrumentation can be limited to simply an inlet temperature monitor. Good control of inlet gas temperature is necessary to avoid destroying the microorganism. Inlet temperature significantly above 105°F (41°C) may indicate a failure in the humidification system.

Inlet Gas Relative Humidity

The relative humidity of the inlet gas stream can be measured using portable instruments, including a simple wet bulb–dry bulb thermometer and battery-powered instruments. Relative humidity in excess of 95% is needed to maintain the necessary water layer over the packing material, which is needed for the microorganisms to be active.

Outlet VOC Concentration

Portable VOC analyzers provide the only direct means of evaluating the ability of the microorganisms to metabolize the organic compounds present in the gas stream. These instruments must be capable of operating in the 10 ppm to 500 ppm concentration range.

High outlet concentrations could occur because of low bed temperature, toxicity of one or more organics in the waste gas stream to the microorganisms, or death of the microorganisms because of excessive temperature and/or loss of moisture in the bed.

Recirculated Liquid pH

The pH of the recirculated water can be measured with a portable pH monitor or even pH paper. Low pH levels indicate the acidification resulting from the presence of sulfur- and chlorine-containing materials in the gas stream. The pH should be in the range of 6 to 8.

Review Problems

Types and Components of Absorbers

1. The gas stream temperature at the scrubber inlet has increased significantly. If the other operating conditions (i.e., liquid flow rate) stay the same, how will this change affect the control efficiency of the absorber system?
 - a. It will increase.
 - b. It will decrease.
 - c. It will remain unchanged.
 - d. No way to predict.
2. Sulfur dioxide absorbed in a packed bed reacts with alkali dissolved in the scrubbing liquid. Does the Henry's Law equilibrium constant limit sulfur dioxide absorption in this system?
 - a. Yes
 - b. No
 - c. Only if the temperature is too high.
 - d. Only if the temperature is too low.
3. What type of spray nozzle is used in most spray-tower absorbers?
 - a. Full cone
 - b. Hollow cone
 - c. Fan
 - d. Two-fluid atomizing
4. What is the typical liquid-to-gas ratio in spray-tower absorbers?
 - a. 5 to 50 gallons/ACF
 - b. 50 to 200 gallons/ACF
 - c. 1 to 5 gallons/1000 ACF
 - d. 5 to 50 gallons/1000 ACF
5. What is the typical liquid-to-gas ratio in a venturi absorber?
 - a. 20 to 100 gallons/ACF
 - b. 100 to 500 gallons/ACF
 - c. 1 to 20 gallons/1000 ACF
 - d. 20 to 50 gallons/1000 ACF
6. What is the primary purpose of the packing material in a packed-bed scrubber?
 - a. To provide liquid surface area for mass transfer
 - b. To provide liquid sheet impaction targets
 - c. To decrease the gas stream velocity
 - d. None of the above

7. What factors affect the performance of spray-tower, packed-bed, tray-tower, and venturi absorbers?
 - a. Gas velocity
 - b. Gas-liquid distribution
 - c. Gas-droplet-size distribution
 - d. All of the above
8. What is the purpose of the mist eliminator? Select all that apply.
 - a. To protect the fan from accumulation of solids
 - b. To minimize the emission of droplets containing solids
 - c. To capture droplets ranging in size from 10 micrometers to 1000 micrometers
 - d. To capture droplets ranging in size from 1 to 10 micrometers
9. What is the typical gas velocity approaching chevron, radial-blade, and mesh-pad mist eliminators?
 - a. 1 to 5 feet per minute
 - b. 5 to 15 feet per minute
 - c. 1 to 5 feet per second
 - d. 5 to 15 feet per second
10. What is the typical pH range in an absorber system?
 - a. 1 to 5
 - b. 5 to 9
 - c. 9 to 14
 - d. None of the above
11. What is the purpose of adding alkali to the recirculating liquid in an absorber system? Select all that apply.
 - a. To protect the absorber materials of construction from corrosion
 - b. To optimize absorption of acid gases
 - c. To optimize droplet size distribution
 - d. To optimize settling rates of suspended solids in clarifiers used to treat the purge stream

Operating Principles of Absorbers

12. A gas is more soluble when _____.
 - a. the absorbent is cold
 - b. the absorbent is hot
 - c. solubility is independent of absorbent temperature
 - d. the liquid surface tension is low

13. Henry's Law usually applies when the gas phase concentration of the pollutant is_____ .
 - a. low
 - b. high
 - c. Henry's Law is independent of the gas phase concentration.
 - d. Impossible to say
14. The Henry's Law constant for compound A is 40, while the value for compound B is 0.4. Which compound is more soluble?
 - a. Compound A
 - b. Compound B
 - c. Both are equally soluble.
 - d. More information is required.
15. A pollutant dissolving into an aqueous absorbent reacts rapidly upon entering the liquid. What factors influence the determination of the necessary liquid-to-gas ratio for this absorber?
 - a. Equilibrium of the gas phase pollutant and the dissolved form of the pollutant
 - b. Adequacy of gas-liquid contact (hydraulic considerations)
 - c. Both a and b
 - d. None of the above
16. When does Henry's Law not apply to absorption processes? Select all that are correct.
 - a. When the gas concentration is high
 - b. When the gas concentration is low
 - c. When there is substantial heat released during dissolution
 - d. None of the above

Capability and Sizing of Absorbers

17. Which factors can cause gas-liquid maldistribution in a packed-bed absorber?
 - a. Inadequate liquid distribution at the top and/or inadequate redistribution between beds in the vertical tower
 - b. Channeling due to plugging in the bed
 - c. Collapse of one or more beds
 - d. All of the above
18. A vertical spray-tower absorber has a gas flow rate of 6000 ACFM. The absorber diameter is 3.5 feet. What is the average velocity through the absorber? Is this velocity within the normal range for a chevron-type (zigzag) mist eliminator?

19. An exhaust stream of 3000 SCFM contains 3% NH_3 by volume. The operator plans to reduce the NH_3 content by 90% by scrubbing with water (no alkaline additives). What is the required liquid flow rate at 1.5 times the minimum liquid-to-gas ratio? Use the following data to solve the problem.

$$\text{Henry's Law constant} = 0.772 \frac{\text{mole fraction } \text{NH}_3 \text{ in gas}}{\text{mole fraction } \text{NH}_3 \text{ in liquid}}$$

$$\text{Liquid density} = 62.4 \text{ lb}_m/\text{ft}^3$$

$$7.48 \text{ gal H}_2\text{O} = 1.00 \text{ ft}^3$$

$$\text{Gas density} = 0.0732 \text{ lb}_m/\text{ft}^3$$

$$\text{Gas temperature} = 20^\circ\text{C}$$

Review Answers

Types and Components of Absorbers

1. The gas stream temperature at the scrubber inlet has increased significantly. If the other operating conditions (i.e., liquid flow rate) stay the same, how will this change affect the control efficiency of the absorber system?
 - b. It will decrease.
2. Sulfur dioxide absorbed in a packed bed reacts with alkali dissolved in the scrubbing liquid. Does the Henry's Law equilibrium constant limit sulfur dioxide absorption in this system?
 - b. No
3. What type of spray nozzle is used in most spray-tower absorbers?
 - a. Full cone
4. What is the typical liquid-to-gas ratio in spray-tower absorbers?
 - a. 5 to 50 gallons/1000 ACF
5. What is the typical liquid-to-gas ratio in venturi absorbers?
 - a. 20 to 50 gallons/1000 ACF
6. What is the primary purpose of the packing material in a packed-bed scrubber?
 - a. To provide liquid surface area for mass transfer
7. What factors affect the performance of spray-tower, packed-bed, tray-tower, and venturi absorbers?
 - a. Gas velocity
 - b. Gas-liquid distribution
8. What is the purpose of the mist eliminator? Select all that apply.
 - a. To protect the fan from accumulation of solids
 - b. To minimize the emission of solids containing droplets
 - c. To capture droplets ranging in size from 10 micrometers to 1000 micrometers
9. What is the typical gas velocity approaching chevron, radial blade, and mesh pad mist eliminators?
 - d. 5 to 15 feet per second
10. What is the typical pH range in an absorber system?

- b. 5 to 9
- 11. What is the purpose of adding alkali to the recirculating liquid in an absorber system? Select all that apply.
 - a. To protect the absorber materials of construction from corrosion
 - b. To optimize absorption of acid gases

Operating Principles of Absorbers

- 12. A gas is more soluble when _____.
 - a. the absorbent is cold
- 13. Henry's Law usually applies when the gas phase concentration of the pollutant is _____.
 - a. low
- 14. The Henry's Law constant for compound A is 40, while the value for compound B is 0.4. Which compound is more soluble?
 - b. Compound B
- 15. A pollutant dissolving into an aqueous absorbent reacts rapidly upon entering the liquid. What factors influence the determination of the necessary liquid-to-gas ratio for this absorber?
 - b. Adequacy of gas-liquid contact (hydraulic considerations)
- 16. When does Henry's Law not apply to absorption processes?
 - a. When the gas concentration is high
 - c. When there is substantial heat released during dissolution

Capability and Sizing of Absorbers

- 17. Which factors can cause gas-liquid maldistribution in a packed-bed absorber?
 - d. All of the above
- 18. A vertical spray-tower absorber has a gas flow rate of 6000 ACFM. The absorber diameter is 3.5 feet. What is the average velocity through the absorber? Is this velocity within the normal range for a chevron-type (zigzag) mist eliminator?
 - a. Yes

Solution:

Calculate the average velocity.

$$\text{Area} = \left(\frac{3.14 (3.5 \text{ ft})^2}{4} \right) = 9.6 \text{ ft}^2$$

$$\text{Velocity} = \text{Gas flow rate/area} = \left(\frac{6,000 \text{ ft}^3/\text{min}}{9.6 \text{ ft}^2} \right) \left(\frac{\text{min}}{60 \text{ sec}} \right) = 10.4 \text{ ft/sec.}$$

This is within the normal range for a chevron-type mist eliminator.

19. An exhaust stream of 3000 SCFM contains 0.3% NH_3 by volume. The operator plans to reduce the NH_3 content by 90% by scrubbing with water (no alkaline additives). What is the required liquid flow rate (gal/min) at 1.5 times the minimum liquid-to-gas ratio? Use the following data to solve the problem.

$$\text{Henry's Law constant} = 0.772 \left(\frac{\text{mole fraction } \text{NH}_3 \text{ in gas}}{\text{mole fraction } \text{NH}_3 \text{ in liquid}} \right)$$

$$\text{Liquid density} = 62.4 \text{ lb}_m/\text{ft}^3$$

$$7.48 \text{ gal H}_2\text{O} = 1.00 \text{ ft}^3$$

$$\text{Gas density} = 0.0732 \text{ lb}_m/\text{ft}^3$$

$$\text{Gas temperature} = 20^\circ\text{C}$$

Solution:

Calculate the equilibrium concentration of NH_3 in water.

$$y^* = Hx$$

$$0.03 \text{ mole fraction } \text{NH}_3 \text{ in gas} = \left(0.772 \frac{\text{mole fraction } \text{SO}_2 \text{ in gas}}{\text{mole fraction } \text{SO}_2 \text{ in liquid}} \right) x$$

$$x = 0.0389 \text{ mole fraction } \text{NH}_3 \text{ in exit liquid}$$

Calculate $(L_m/G_m)_{\min}$ using Equation 5-9.

$$Y_1 - Y_2 = (L_m/G_m)(X_1 - X_2)$$

$$G_m = 3000 \text{ SCFM}(\text{lb mole gas}/385.4 \text{ SCF}) = 7.78 \text{ lb mole/min}$$

$$\begin{aligned} (L_m)_{\min} &= [G_m(Y_1 - Y_2)/(X_1 - X_2)] = [7.78(0.03 - 0.003)/(0.0389 - 0)] \\ &= 5.4 \text{ lb mol/min} \end{aligned}$$

$$L_m = 1.5 (L_m)_{\min} = 1.5(5.4) = 8.1 \text{ lb mole/min}$$

$$(8.1 \text{ lb mole/min})(18 \text{ lb/lb mole})(\text{ft}^3/62.4 \text{ lb})(7.48 \text{ gal/ ft}^3) = 17.5 \text{ gpm}$$

References

1. Bhatia, M. V. Packed Tower and Absorption Design. In *Air Pollution Control and Design Handbook*; Cheremisinoff, P.N., Young, R.A., Eds.; Marcel Dekker, Inc.: New York, 1977.
2. Leson, G.; Tabstabal, F.; Winer, A. *Biofiltration: An Innovative Air Pollution Control Technology for VOC Emissions*; Paper 92-116.03; 85th Annual Meeting & Exhibition of the Air & Waste Management Association, Kansas City, Missouri, June 21-26, 1992.
3. Van Lith, C. *Design Criteria for Biofilters*; Paper 165.5; 82nd Annual Meeting & Exhibition of the Air & Waste Management Association, Anaheim, CA, June 25-30, 1989.
4. Bohn, H. Consider Biofiltration for Decontaminating Gases. *Chemical Engineering Progress*: April 1992, 34-40.
5. Heuckeroth, R. Biofilters Provide New Options to Control Air Emissions. *The National Environmental Journal*: November/December 1993, 20-22.
6. Kister, H.Z.; Gill, D.R. Predict Flood Point and Pressure Drop for Modern Random Packings. *Chemical Engineering Progress*: February 1991, 32-42.
7. Strigle, R. *Random Packings and Packed Tower*; Gulf Publishing: Houston, 1987.
8. Perry, J. H., Ed. *Chemical Engineers Handbook*, 5th ed.; McGraw-Hill: New York, 1973.
9. Sherwood, T. K.; Pigford, R.L. *Absorption and Extraction*; McGraw-Hill: New York, 1952.
10. McCabe, W. L.; Smith, C. J. *Unit Operations of Chemical Engineering*; McGraw-Hill: New York, 1967.
11. U.S. Environmental Protection Agency. *Wet Scrubber System Study*; NTIS Report PB-213016; Research Triangle Park, NC, 1972.
12. Shifftner, K.; Hesketh, H. *Wet Scrubbers*; Ann Arbor Science Publishers: Ann Arbor, MI, 1983.
13. Kimre, Inc. Undated literature.